NASA/CP—2000-210472/VOL1

1999 NASA Seal/Secondary Air System Workshop

October 2000

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1999 NASA Seal/Secondary Air System Workshop

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Cleveland, Ohio
October 28–29, 1999

National Aeronautics and
Space Administration

Glenn Research Center

October 2000

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Executive Summary
Volume 1

The 1999 NASA Seal/Secondary Air System Workshop was divided into four areas: (i) overviews of the government-sponsored gas turbine programs (NASA Ultra Efficient Engine Technology program and DOE Advanced Turbine System program) and the general aviation program (GAP) with emphasis on program goals and seal needs; (ii) turbine engine seal issues from the perspective of an airline customer (i.e., United Airlines); (iii) sealing concepts, methods and results including experimental facilities and numerical predictions; and (iv) reviews of seal requirements for next generation aerospace vehicles (Trailblazer, Bantam and X-38).

Overviews of the NASA Ultra Efficient Engine Technology (UEET) program and the DOE Advanced Turbine System (ATS) program work, illustrate for the reader the importance of advanced technologies, including seals, in meeting future engine systems efficiency and emissions goals. The NASA UEET program goals include an 8 to 15 percent reduction in fuel burn, a 15 percent reduction in CO_2, a 70 percent reduction in NO_x, CO, and unburned hydrocarbons, and a 30 dB noise reduction relative to program baselines. The ATS program uses aero-derivative technologies and several other new technologies that boost the power plant combined cycle efficiencies to 60 percent with a long-range vision of fuel cell topping efficiencies to 80 percent while reducing the cost of electricity to the consumer. The major players are GE and Siemens-Westinghouse. On the opposite end of the size/weight scale, one finds the general aviation program (GAP). The Teledyne 200-hp-IC-4-cylinder-liquid cooled diesel targets the propeller driven private-aviation segment while Williams's 700-pound-thrust, 100-pound jet engine with a bypass ratio of 4 targets the private jet industry.

Several seal companies provided updates on their respective sealing technologies. The NASA funded GE/Stein Seal team has successfully demonstrated a large (3' dia.) aspirating seal that can withstand all anticipated pressures, speeds and rotor run-outs anticipated for a GE90 L.P. turbine balance piston. Laboratory tests at GE-CRD demonstrated the seal could accommodate a 1-in-5000 hour severe maneuver tilt-load without rubbing, in which the rotor tilts 0.080" toward the seal face! The Allied Signal/NASA GRC finger seal development program overcame finger seal hysteresis through the use of pressure-balancing techniques. Finger seal endurance tests demonstrated finger seal operations for 120 hours. Mohawk presented a foil seal arrangement that applies foil bearing technology to arrive at a non-contracting very low-leakage seal. This foil seal is being developed by Mohawk under a NASA SBIR contract and exploits NASA Glenn's advanced solid film lubricant developments, presented by Christopher DellaCorte. Successful demonstration of the rope-seals to extreme temperatures (5500 °F) for short durations provide a new form of very high temperature thermal barrier for future Shuttle solid rocket motor nozzle joints. Leaf, reinforced cloth, face and brush sealing concepts proposed or used in industrial (aeroderivative) gas turbines show promise in increasing efficiency with long life. Interactive cavity and blade/vane time accurate numerical simulations are necessary for accurate performance prediction and secondary and purge air management. Numerical codes and methods are now capable of providing engine performance and analysis simulations (NPSS). Aerospace programs that require advanced sealing concepts to fly include: Trailblazer (rocket-based combined cycle (RBCC) demonstrator); Bantam launch vehicle ($1k/lb-payload in ten-year study concept); and the X-38, a prototype for the Space Station Emergency Crew return vehicle.

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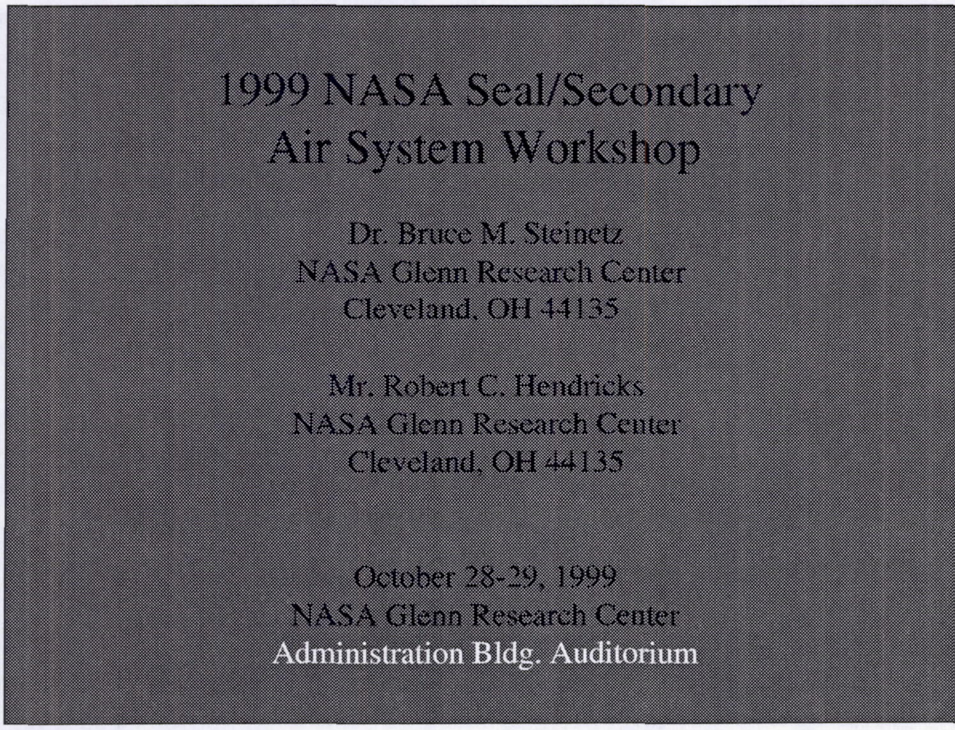
1999 NASA SEAL/SECONDARY AIR SYSTEM WORKSHOP

Bruce M. Steinetz and Robert C. Hendricks
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio



NASA Glenn hosted the Seals/Secondary Air System Workshop on October 28-29, 1999. Each year NASA and our industry and university partners share their respective seal technology development. We use these workshops as a technical forum to exchange recent advancements and "lessons-learned" in advancing seal technology and solving problems of common interest. As in the past we are publishing two volumes. Volume 1 will be publicly available and will be made available on-line through the web page address listed at the end of this chapter. Volume 2 will be restricted under International Traffic and Arms Regulations (I.T.A.R.)

In this conference participants gained an appreciation of NASA's new Ultra Efficient Engine Technology (UEET) program and how this program will be parterning with ongoing DOE –industrial power production and DOD- military aircraft engine programs. In addition to gaining a deeper understanding into sealing advancements and challenges that lie ahead, participants gained new working and personal relationships with the attendees.

When the seals and secondary fluid management program was initiated, the emphasis was on rocket engines with spinoffs to gas turbines. Today, the opposite is true and we are, again building our involvement in the rocket engine and space vehicle demonstration programs.

AST Program Goals

- **Reduce commercial aircraft direct operating costs including interest (DOC+I) by:**
  - **3% (large engines) and 5% (regional engines)**
- **Reduce engine fuel burn up by:**
  - **8% (large engines) and 10% (regional engines)**
- **Reduce engine oxides of nitrogen (NOx) emissions by greater 50%**
- **Reduce airport noise by 7 dB, or about three-quarters reduction in acoustic energy**
- **Entry into service: 2005 - 2006**

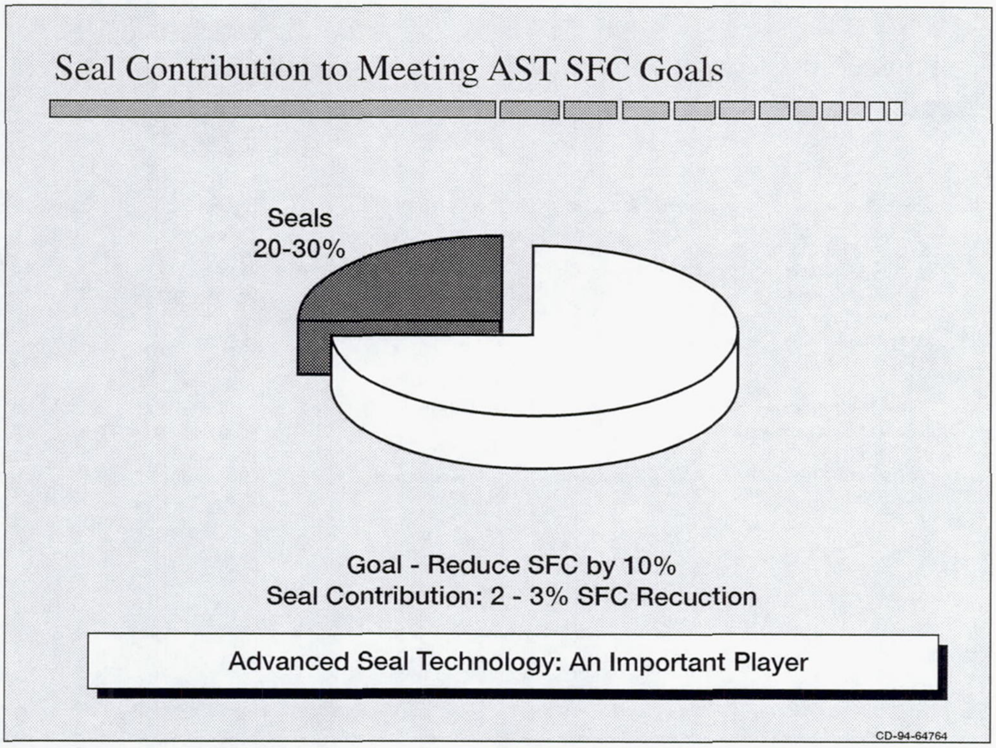
Recognizing the need to reduce aircraft operation costs, NASA established several programs to improve both engine and vehicle performances and lower direct operating costs (DOC). The Advanced Subsonic Technology Program (1995-1999) targeted the goals shown in the chart (Steinetz and Hendricks, 1998).

Cycle studies have shown the benefits of increasing engine pressure ratios and cycle temperatures to decrease engine weight and improve performance in next generation turbine engines. Advanced seals have been identified as critical in meeting engine goals for specific fuel consumption, thrust-to-weight, emissions, durability and operating costs. NASA and the industry are identifying and developing engine and sealing technologies that will result in dramatic improvements and address each of the goals for engines entering service in the 2005-2006 time frame.

Engine Study Results: Expected Seal Technology Payoffs

Seal Technology	Study Engine	Company	System Level Benefits
Large Diameter Aspirating Seals (Multiple Locations)	**GE90/Transport**	**GE**	**-1.86% SFC** **-0.69% DOC+I**
Interstage Seals (Multiple Locations)	**GE90/Transport**	**GE**	**-1.25% SFC** **-0.36% DOC+I**
Film Riding Seals (Turbine Inter-stage seals)	**AST Regional/AE3007**	**Allison**	**> -0.9% SFC** **> -0.89% DOC+I**
Advanced Finger Seals	**AST Regional**	**AlliedSignal**	**-1.4% SFC** **-0.7% DOC+I**

General Electric, Allison and AlliedSignal Engines all performed detailed engine system studies to assess the potential benefits of implementing advanced seals. The study results were compelling. Implementing advanced seals into modern turbine engines will net large reductions in both specific fuel consumption (SFC) and direct operating costs including interest (DOC+I) as shown in the chart (Steinetz et al, 1998).

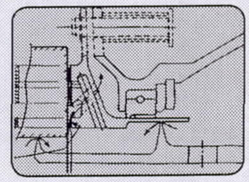


Applying the seals proposed in the previous slide to just several engine locations would reduce SFC 2 to 3% . This represents a significant (20-30%) contribution toward meeting the overall goals of the AST program.

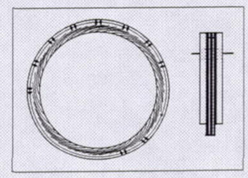
AST Descoped Seal Program

<u>General Electric</u>
Large Diameter Seal Development
#1 Aspirating Seal -
G.E. C.R.D. Rig Tests. CFD Analysis, Engine Test (Option)

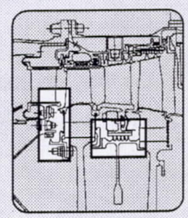
#2 Low Hysteresis Brush Seal Development
Rig Tests, Engine Test



<u>Allied Signal</u>
Low-Hysteresis Finger Seal Development
Rig Tests (NASA LeRC) - Baseline & Low Hysteresis Designs
- Performance & Endurance Tests



<u>Allison Engine Company</u>
Seal - Secondary Air System Design



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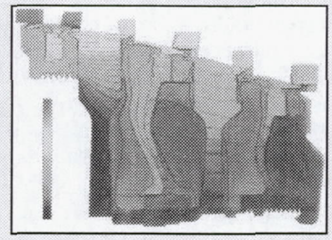
NASA partnered with several companies to evaluate respective advanced sealing technologies as explained on these two charts.

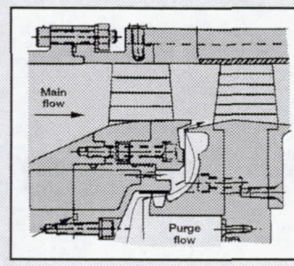
GE investigated large diameter aspirating seals and brush seals for the balance piston location in the low-pressure turbine. AlliedSignal investigated a new, low-hysteresis finger seal design. AlliedSignal and NASA performed rig performance and limited endurance tests in NASA's Turbine Seal test Rig. Allison Engine performed a detailed seal/secondary air system design to evaluate benefits of advanced seals throughout their AE3007 engine (Munson, 1999).

AST Descoped Seal Program (cont'd)

CFD - Research Center

Develop coupled secondary air (SCISEAL)/main flow path (TURBO) solution technique to predict complex cavity/main flow path interactions





UTRC

— Measure steady/unsteady turbine rim seal/cavity flows for baseline rim seal geometry

— Develop optimized (reduced flow) rim seal

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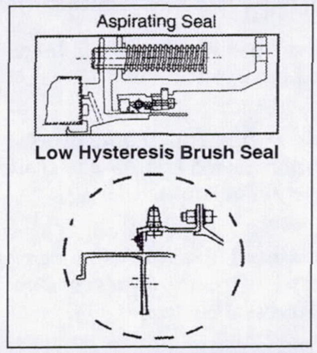
NASA contracted CFDRC to develop a coupled secondary air/main flow path solver to investigate complex turbine cavity/rim seal/main flow phenomenon. CFDRC coupled the CFDRC/NASA code SCISEAl to the Mississippi State Univ. code TURBO to perform these unsteady calculations.

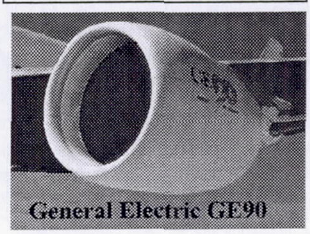
NASA also contracted with UTRC to measure the steady/unsteady turbine rim seal/cavity flows to assess the performance of both baseline turbine rim seal and optimized (reduced flow) rim seal geometries.

Highlights of AST Seal Program Accomplishments: GE

General Electric

- **Successfully demonstrated 36" Aspirating seal**
  - **Leakage <1/5th labyrinth seal**
  - **Operates without contact under severe conditions:**
    - **10 mil TIR**
    - **0.25°/0.8 sec. Tilt Maneuver loads (0.08" deflection!)**
- **Successfully demonstrated 36" Low Hysteresis Brush seal in GE90 demonstrator**
  - **30% leakage reduction over previous 2-stage brush seal**
  - **Leakage <1/2 labyrinth seal**
  - **Survived punishing GE90 HCF durability test**




General Electric GE90

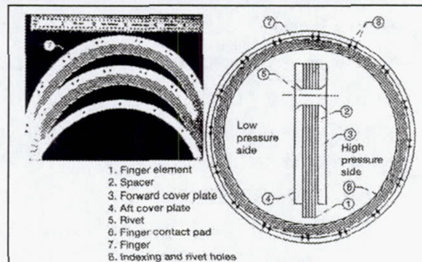
Aspirating Seal: General Electric is developing a low leakage aspirating face seal for a number of locations within modern turbine applications. This seal shows promise both for compressor discharge and balance piston locations. The seal consists of an axially translating mechanical face that seals the face of a high speed rotor. The face rides on a hydrostatic cushion of air generated by air supplied through ports on the seal face supplied by air from the high pressure side of the seal. The small clearance (0.001-0.002 in.) between the seal and rotor results in low leakage (1/5th that of new labyrinth seals) and applied to 3 locations in a GE90 engine can lead to >1.8% SFC reduction. GE Corporate Research and Development tested the seal under a number of conditions to demonstrate the seal's rotor tracking ability. The seal was able to follow a 0.010 in. rotor face total indicator run-out (TIR) and could dynamically follow a 0.25° tilt maneuver (simulating a hard maneuver load) all without face seal contact (see also Turnquist in the current Seal Workshop Proceedings for further details). GE and NASA are seeking to demonstrate this seal on a demonstrator engine under a future program.

Low Hysteresis Brush Seal: A single stage low-hysteresis brush seal was developed for modern engine applications under the NASA AST program. This program showed that a single stage low-hysteresis seal was an improvement over the existing two-stage brush seal in the GE90 engine. Sub-scale (8 9/16" diameter) single-stage seals were used to pre-screen different seal design and material combinations. Lessons learned from these tests were subsequently used to design/fabricate 36" brush seals that were installed and tested on a GE90 demonstrator ground-based engine. The single stage brush seal performed well under very aggressive high cycle fatigue tests in the GE90. The single stage seal (with advanced design features) leakage flow was 30% less than the previous 2-stage brush seal and was less than half that of a competing new labyrinth seal. The single stage low-hysteresis brush seal survived the punishing GE90 HCF durability test. (see also presentation by Tseng in the current Seal Workshop Proceedings for further details).

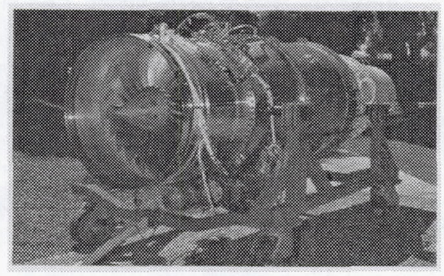
Highlights of AST Seal Program Accomplishments: AlliedSignal

<u>AlliedSignal</u>

- **Developed low-hysteresis finger seal for turbine applications**
- **Low cost photo-etching process demonstrated resulting in seal costs a fraction of brush seals**
- **Pressure balanced design demonstrated very low hysteresis in repeated NASA Glenn seal rig testing**
- **Leakage 20-70% less than typical four-knife labyrinth seal (0.005" clearance)**
- **Extensive analytical work and rig testing has resulted in finger seal ready for consideration for future engine testing. (ref AS900 Engine)**



Low Hysteresis finger seal

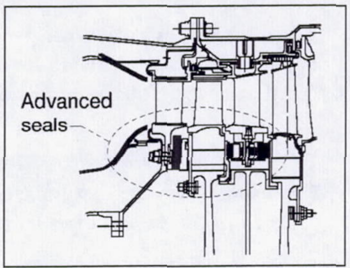


AlliedSignal AS900

Under the AST program, AlliedSignal and NASA have developed a low-hysteresis finger seal for turbine applications (Arora et al, 1999). The finger seal is similar in general configuration to a brush seal, but functions in a very different manner. Instead of a random array of fine wires, the finger seal uses a stack of precision machined sheet stock laminates. Each laminate is machined to create a series of fingers around the inner diameter that follows shaft growth or movement during engine operation. Successive laminates are indexed to cover the finger spaces in the previous laminate layer.

The finger seal exhibits low-leakage (20-70% less than a 4 tooth labyrinth seal with a tight 0.005" clearance). Laminates made using low cost photo-etching technique results in a seal that costs a fraction that of brush seals. The AST finger seal program developed a balanced pressure finger seal design that essentially eliminates hysteresis or frictional drag between the radially moving laminates and the downstream backing plates that had caused unacceptably high leakage in previous finger seal designs. This frictional drag had prevented the laminates from moving radially inward to follow the shaft after a transient event or during rotor slow-down conditions (see also presentation by Arora and Proctor in the 1999 Seal Workshop Proceedings for further details).

Highlights of AST Seal Program Accomplishments: Allison



Allison Engines

- **Conducted realistic study of gas turbine engine to determine effect of advanced seals on the total system**
- **Determined advanced seal requirements**
- **Determined cost/benefit of advanced seals**

Benefits:

- **Constant rotor inlet temperature (RIT) (rubber airframe/fixed engine):**
  - **+1.9% Thrust-to-weight**
  - **-0.7 % Mission Fuel Burn**
- **Constant Thrust**
  - **Reduces RIT by approximately 20°F - increases blade life by more than 50%**
  - **Reduces fuel burn by approximately 0.7%**
  - **Reduces emissions of CO and unburned hydrocarbons**
  - **Results in DOC reduction of approximately 0.9%: 18% of NASA AST goal for regional engine applications.**

Allison performed a detailed secondary air system study to identify potential locations where the greatest performance improvements could be made implementing advanced seals. This study examined in great detail the benefits of applying advanced seals in the high pressure turbine region of the engine. Low leakage film-riding seals cut in half the estimated 4% cycle air currently used to purge the high pressure turbine cavities in the AE3007 regional jet engine. These savings can be applied in one of several ways. Holding rotor inlet temperature (RIT) constant the engine mission fuel burn can be reduced 0.7%, or thrust-to-weight could be increased 1.9%. Alternatively, RIT could be lowered 20°F resulting in a 50% increase in turbine blade life reducing overall regional aircraft maintenance and fuel burn direct operating costs 0.9% for a 600 nautical mile mission. Thermal, structural, secondary-air systems, safety (seal failure and effect), and emissions analyses were also performed showing that the proposed design was feasible (Munson, 1999).

Other Turbine Seal Accomplishments

- Completed fabrication/received delivery of state-of-the-art turbine seal test rig capable of testing seals under all anticipated IHPTET/VAATE/NASA speed and temperature (1500 °F) conditions.

- Completed coupling of TURBO (main-flow path solver) to SCISEAL (Seal/secondary air system solver) to investigate turbine/rim seal flow interactions and aid in the design of more robust rim seal systems.

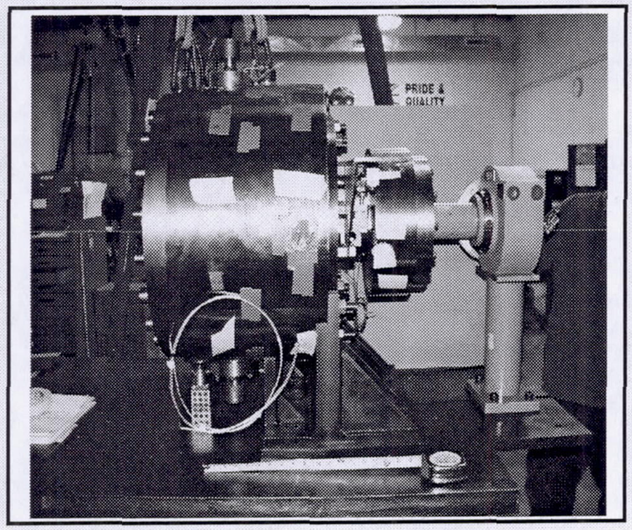
- Awarded SBIR Phase I to Mohawk Innovative Technology to investigate film-riding compliant foil seal (derivative of foil bearing technology) with potential for very low leakage and non-contacting operation.

The high temperature, high speed turbine seal rig fabrication has been completed. Installation of this state-of-the-art test rig is underway.

CFD- Research Corporation has completed the coupling of TURBO and SCISEAL for analyzing the complex main stream (TURBO) and secondary air stream (SCISEAL) interactions, including the effects of vane/blade wake interactions. The package can analyze flows from the engine centerline through the turbine rim seal location and through main flow path.

NASA has awarded to Mohawk Innovative Technology an SBIR Phase I to investigate film-riding compliant foil seals (see presentation by Salehi and Heshmat in the current 1999 Seal Workshop Proceedings). Foil seals are derived from foil bearing technology and block flow between high and low pressure cavities through very narrow gaps between the shaft and the foil. The hydrodynamic lift between the seal and the shaft prevents rotor-seal contact during operation. High temperature solid film lubricants applied to the shaft prevent wear during start-up and shut-down when limited contact occurs (see presentation by DellaCorte in the current 1999 Seal Workshop Proceedings).

High Temperature Seal Rig Fabrication Complete



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The high temperature, high speed turbine seal rig is shown after fabrication and assembly were completed at the vendor.

Why is Seal Development for Key for UEET?

Increase Efficiency:

- **Minimum parasitic leakage is required to meet efficiency/fuel burn goals**

Increase Stage Loading:

- **Minimum blade tip loss, interstage leakage critical to meeting stage loading goals**

Reduced Emissions:

- **Minimum parasitic leakage translates into minimum fuel burn which translates into minimum emissions across the board:**
  - » **NOx**
  - » **CO**
  - » **CO2**
  - » **Water vapor**

NASA has begun in FY00 a new program entitled Ultra Efficient Engine Technology (UEET) program whose goal is to dramatically improve engine efficiency and reduce emissions through advanced turbomachinery concepts.

The NASA UEET program goals include an 8-15% reduction in fuel burn, a 15% reduction in CO_2, a 70% reduction in NO_x, CO and unburned hydrocarbons, and a 30 dB noise reduction, relative to program baselines. Under the UEET program, NASA has contracted with General Electric to perform a GE90 engine test to demonstrate the aspirating seal developed and laboratory-tested in the AST program. NASA has contracted with PW/Stein Seal to develop advanced carbon seals. Other seal development programs are under discussion with program officials.

Turbine Engine Seal Summary

- NASA and industry partners are pursuing engine performance advancements to reduce fuel burn, reduce operating costs, and ensure insustry competitiveness into the next century and beyond.

- Advancements in seal technology will play an important role in achieving performance goals.

- Significant reductions in SFC are possible through implementing advanced seal technology. Engine studies show that over 2.5% reduction in SFC is possible applying advanced seals to a few locations.

- Costs of developing advanced engine seals are a small fraction of re-designing & re-qualifying complete compressor or turbine components with comparable performance improvements.

Engine designers are re-evaluating all aspects of turbine engines to meet the efficiency, performance and operating cost goals set for next generation turbine engines. A comprehensive survey was made of cycle losses in terms of leakages in modern jet engines such as the Allison Engine AE3007 (Munson, 1999), the GE90 (Tseng, in the current NASA Seal Workshop Proceedings) and an AlliedSignal business engine (Arora, 1999). The survey showed that large performance gains were possible in applying advanced seals in several key locations in the engine.

Structural Seal Accomplishments

Thermal Barrier Development

- **Proved feasibility of NASA Glenn developed Thermal Barrier in a 1/5th Scale Reusable Solid Rocket Motor Firing. Blocked hot gas and soot from reaching the Viton O-ring. Viton O-ring and thermal barrier in "like-new" condition after the test.**

Space Vehicle Control Surface Seal Development

- **Completed design/began fabrication of control surface seal test apparatus to evaluate seal thermal resistance to re-entry level heating rates in Ames Arcjet Tunnel for BANTAM/Spaceliner-100, X-38 (Station emergency escape vehicle demonstrator), X-37 (Space operations vehicle).**

NASA Glenn is also developing structural seals for demanding aero- and space applications.

The NASA Glenn developed braided carbon fiber thermal barrier is the primary candidate being considered by NASA and Thiokol for the redesign of the Space Shuttle RSRM nozzle-to-case joint and for nozzle joint 2 to prevent Viton O-ring damage. Incorporation of the NASA Glenn developed braided carbon fiber thermal barrier into the nozzle joints of the Space Shuttle RSRMs would eliminate hot gas penetration to nozzle joint O-rings and prevent extensive reviews that delay shuttle launches. On August 10, a NASA Glenn developed braided carbon fiber thermal barrier was successfully evaluated in an MNASA reusable solid rocket motor (RSRM) at NASA Marshall. The MNASA RSRM is a 1/5th-scale version of the full-scale RSRMs used to launch the space shuttle. Tested in a redesigned nozzle-to-case joint, an intentional flaw in the nozzle insulation allowed hot combustion gases to reach the thermal barrier. Soot was observed on hardware upstream of the thermal barrier, but none was seen on the downstream side. Post-test inspection revealed no damage or erosion to either the thermal barrier or to downstream O-rings that the thermal barrier is designed to protect. (see presentation by Steinetz and Dunlap in the current 1999 Seal Workshop Proceedings for further details).

NASA Glenn and Boeing are developing control surface seals for advanced re-entry vehicle systems. (see presentation by Verzimnieks in the current 1999 Seal Workshop Proceedings for further details)

BANTAM Advanced High Temperature Structural Seals

Objective

Advanced control surface seal concepts will be investigated and proven using appropriate high temperature test facilities

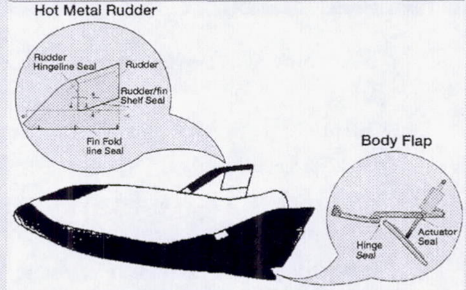
- Structural seals will be developed in concert with advanced heat-resistant composite elements being developed for advanced TPS structural concepts.

Benefits

Enabling Technology: Seals are enabling technology for advanced space launch vehicles, (e.g.: rudder; fin; body-flap; etc.)

- **Weight/Performance/Cost:** High temperature seals permit lower profile TPS, more aggressive structural concepts saving weight/enhancing performance/saving payload-to-orbit costs. Eliminating the need to replace seals between missions enables Bantam to meet cost goals.
- **Safety:** Robust seals increase mission safety and reliability

Dr. Bruce M. Steinetz (216) 433-3302
bruce.steinetz@grc.nasa.gov
NASA Glenn Research Center



Candidate Seals for Evaluation: X38 Case Study

Milestones:

FY99	Establish seal design requirements
FY 00	Complete fabrication/feasibility-screening of leading seal candidates
FY01	Demonstrate technology under simulated environments: Vibro-acoustic; Arc-jet tests.

Resources:

FY	99	00	01
Budget($K)	242	344	344

Task Objective

This effort addresses the development of high temperature structural seals for control surfaces for the Bantam/Spaceliner-100 reusable launch vehicle. Successful development will contribute significantly to the mission goal of reducing launch cost for small, 200-300-pound payloads. Development of high temperature seals is mission enabling. For instance, ineffective control surface seals can result in high temperature (3100°F) flows in the elevon area exceeding structural material limits with a potential for loss of control surface and possibly entire vehicle. Also, longer sealing life will allow use for many missions before replacement. All of this contributes to the reduction of hardware, operation and launch costs.

Scope

This effort provides for the analysis, design, fabrication and testing of advanced structural seal concepts. Key to the success of this program will be use of emergent materials in combinations that will result in durable, feasible, and affordable seal designs. At the completion of the program, a matrix of seals and seal material combinations will have been developed for a range of aerothermal environments for a wide variety of advanced control surface applications (Spaceliner-100, X38, X37, etc). Testing will include thermal and mechanical loadings and arc-jet exposures. Aerothermal analysis methods will be applied early in the program to design the seals and will be validated by comparing the predicted and measured seal thermal responses of the validation seals in arc-jet tests (see also presentation by Verzemnieks and Newquist in the current 1999 Seal Workshop Proceedings for further details).

NASA Seals Web Sites

- **Turbine Seal Development**

http:/www.grc.nasa.gov/WWW/TurbineSeal/TurbineSeal.html
NASA Technical Papers
Workshop Proceedings

- **Braided Rope Seal Development**

http://www.grc.nasa.gov/WWW/structuralseal/
NASA Technical Papers
Discussion
http://www/grc.nasa.gov/WWW/TU/InventYr/1996Inv_Yr.htm

The Seal Team maintains three web pages to disseminate publicly available information in the areas of turbine engine and structural seal development. People interested in these web sites can visit them at the addresses indicated above.

References

- Arora G.K., Proctor, M.P., Steinetz, B.M. and Delgado, I.R., 1999 " Pressure Balanced, Low Hysteresis Finger Seal Test Results," NASA TM-1999-209191, AIAA-99-2686.
- Munson,. J.H., 1999, "Advanced Subsonic Transport Task 8: Advanced Seals and Secondary Airflow Systems," Final Report, Contract NAS3-27725, November, Allison EDR-18602.
- Steinetz B.M., Hendricks, R.C., and Munson, J.H., 1998 "Advanced Seal Technology Role in Meeting Next Generation Turbine Engine Goals," NASA TM-1998-206961.
- Tseng, T.W., Short, J.F., and Steinetz, B.M., 1999, "Development of a Low Hysteresis Brush Seal for Modern Engine Applications," AIAA 99-2683.

OVERVIEW OF ULTRA-EFFICIENT ENGINE TECHNOLOGY (UEET) PROGRAM

Joe Shaw
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio

UEET

Overview of

Ultra-Efficient Engine Technology (UEET) Program

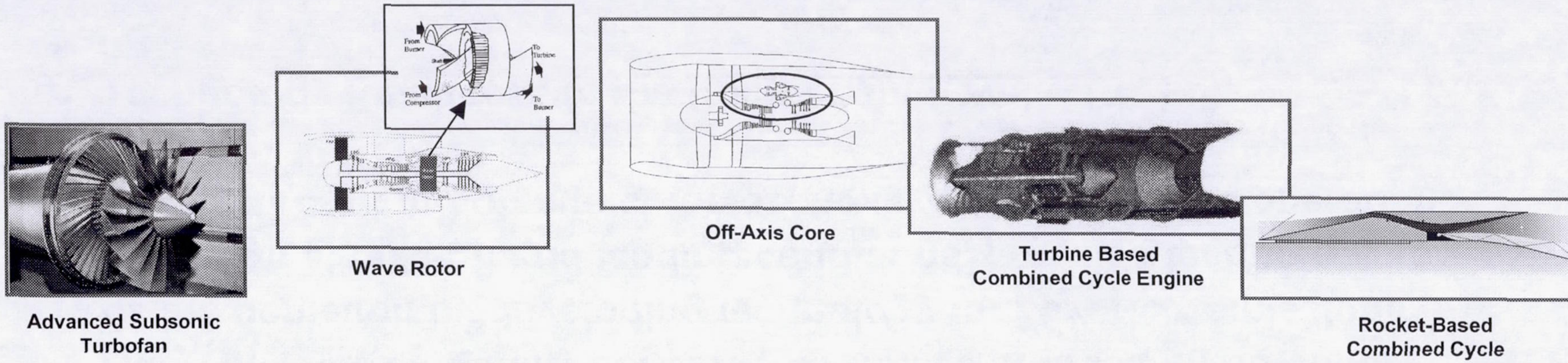
Joe Shaw
Chief, UEET Program Office
NASA Glenn Research Center
Cleveland, OH 44135

UEET Administrator's Charge to NASA Glenn

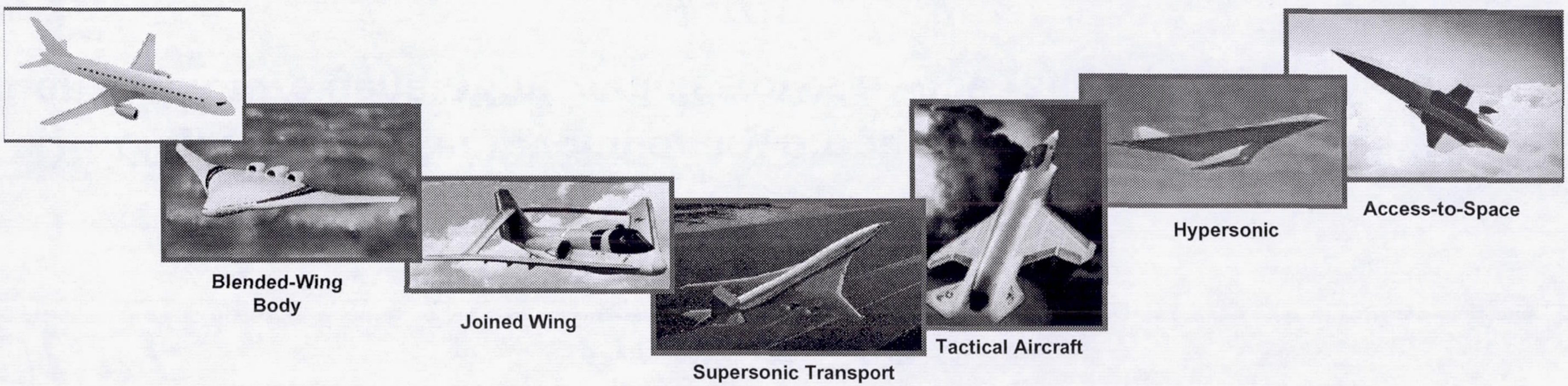
Administrator's November 20, 1998 charge to NASA Glenn.....

Plan a 5 yr. engine technology program that will enable next generation engines for both commercial and military applications. Emphasize revolutionary technologies that will enable future subsonic and high-speed applications. Actively seek collaboration with the DOD.

UEET Vision Statement (Draft)



Develop and transfer revolutionary propulsion technologies that will enable future generation vehicles over a wide range of flight speeds.



UEET **Program Goals**

Develop and transfer revolutionary propulsion technologies that will enable future generation vehicles over a wide range of flight speeds.

- **Address long term aviation growth potential without impact on climate by providing technology for dramatic increases in efficiency to enable reductions in CO_2 based on an overall fuel savings goal of up to 15%.**
- **Address local air quality concerns as well as addressing potential ozone depletion by developing technology for 70% NOx emissions reduction at take-off and landing conditions, and also technology to enable aircraft to not impact the ozone layer during cruise operation.**
- **Technology Readiness to the Component Level (TRL 4-5).**

UEET

Investment Areas

Ultra-Efficient Engine Technology

Combustion
- Ultra-Low NOX Combustors
- Particulates/ Aerosols & other Emittents

Turbomachinery
- Fans
- Highly Loaded Compressors
- Highly Loaded/ Coupled HP/LP Turbines

Materials & Structures
- CMC Liner & Vane
- Adv. Materials
  - Disk
  - Airfoils
- Light Weight Nozzle Structure
- High Temperature PMC

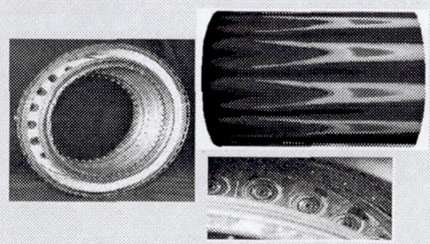
Propulsion/ Airframe Integration
- Smart Nacelle technology
- Advanced PAI Methodologies Development
- Conventional/unconventional installations

System Integration & Assessment
- System Analysis and Benefit Assessment
- Technology Requirements
- Simulations to Reduce Testing
- Assessment including Environmental Impact

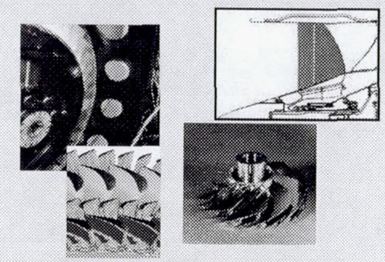
A Portfolio of Enabling Technologies for Future Generations of High Performance Engines (Commercial and Military)

UEET Investment Areas for Baseline Program

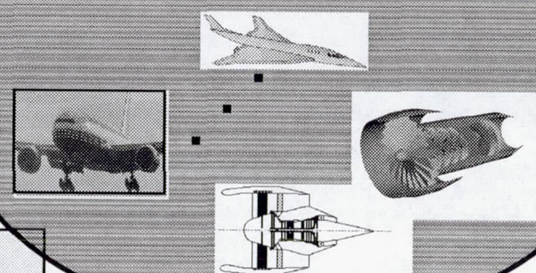
Combustion



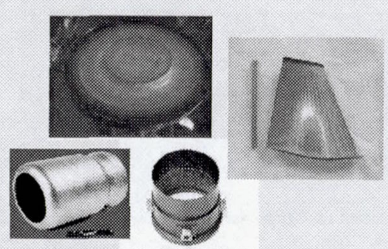
Turbomachinery



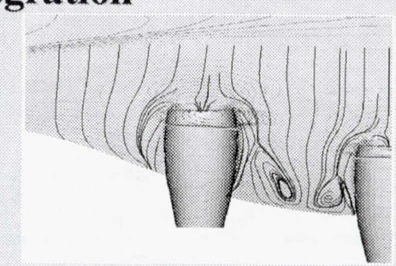
System Integration



Materials and Structures



Propulsion/Airframe Integration



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NASA's Technology Readiness Level (TRL) Scale Applied to UEET Program

TRL	General NASA Definition
9	Actual system "flight proven" on operational flight
8	Actual system completed and "flight qualified" through test and demonstration
7	System prototype demonstrated in flight environment
6	System/subsystem model or prototype demonstrated/validated in a relevant environment
5	Component and/or breadboard verification in a relevant environment
4	Component and/or breadboard test in a laboratory environment
3	Analytical and experimental critical function, or characteristic proof-of-concept
2	Technology concept and/or application formulated (candidate selected)
1	Basic principles observed and reported

System Test and Operations

System/Subsystem Development

Technology Demonstration

Technology Development

Research to Prove Feasibility

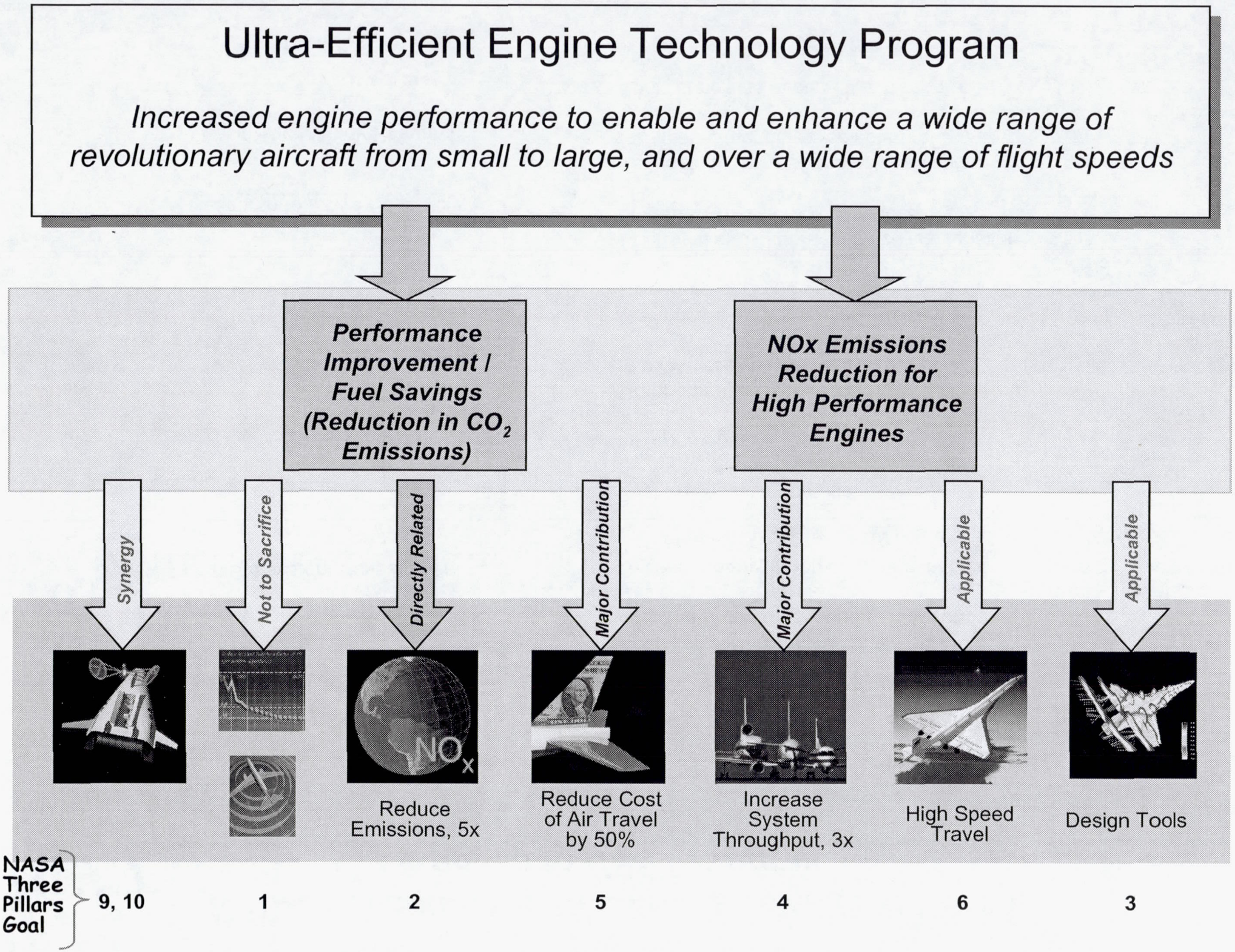
Basic Technology Research

Industry Role

Government Role

UEET Program

HSR and AST Planned Span



Ultra-Efficient Engine Technology Program
Increased engine performance to enable and enhance a wide range of revolutionary aircraft from small to large, and over a wide range of flight speeds
Performance Improvement / Fuel Savings (Reduction in CO_2 Emissions)
NOx Emissions Reduction for High Performance Engines
Synergy
Not to Sacrifice
Directly Related
Major Contribution
Major Contribution
Applicable
Applicable
NOx
Reduce Emissions, 5x
Reduce Cost of Air Travel by 50%
Increase System Throughput, 3x
High Speed Travel
Design Tools
NASA Three Pillars Goal
9, 10
1
2
5
4
6
3

UEET Overview

Goal

Increase Turbine Engine Performance and Efficiency (Fuel Burn 8-15% Reduction), Reduce Emissions (70% Reduction in LTO Levels)

Goal Factors / **Objectives**

Propulsion System Weight
- Increase Stage Loading
- Lightweight Materials and Structural Concepts

Emissions Production
- Ultra Low NOx Combustor
- Characterization of Particulates Aerosol Production
- Emissions Impact

Cycle Performance
- High Cycle Temperature / Pressure
- High Temperature Materials
- Increase Cooling Effectiveness

Installation Drag
- Low Drag Nacelles

Component Efficiency
- Component Efficiency Improvements

UEET

Work Breakdown Structure

1.0 Systems Assessment

2.0 Emissions Reduction

3.0 Highly Loaded Turbomachinery

4.0 Materials and Structures for High Performance

5.0 Propulsion Airframe Integration

6.0 Program Management

UEET Level I Milestone Schedule

FY	2000	2001	2002	2003	2004
1.0 Systems Assessment	Preliminary Technology Benefits Assessment	Propulsion System(s) Conceptual Definition	Interim Technology Assessments	Initial High Fidelity System Simulation	Final Technology Assessment
2.0 Emissions Reduction	Flametube Eval's. of 70% LTO NOx Concepts		Sector Eval's. of 70% LTO NOx Configurations	Sector Demo (Cruise NOx); Init. Annular Rig Demos (Lg. Eng.) - 70% LTO NOx Configs.	CMC Annular Rig Demo - 70% LTO NOx; Physics Based Prediction Codes Validated (Comb.)
3.0 Highly Loaded Turbomachinery	Flow Control Concept(s) Selected - Fan, Compressor	Flow Control Concept(s) Selected - Turbine	Flow Control POC		Physics Based Prediction Codes Validated (T/M)
Fan					Flow Control Validation
Compressor					Highly Loaded Multistage Validation
Turbine					Highly Loaded HP/LP Validation
4.0 Materials & Structures for High Performance	Ceramic Thermal Barrier Coating Concept(s) Selection	1350°F Turbomachinery Disk Alloy	Mat'l Sys. for CMC Turbine Vane; Ceramic Thermal Barrier Coating / Process; Eng. Demo of PMC Structure	CMC Complex Part Demo; 1400°F Disk Process	High Temperature Materials Capabilities Demos.
5.0 Propulsion Airframe Integration	Methods Downselect		Eval. of Active Flow Control Concepts	Init. High Re Validation of Method	Final High Re Validation of Method; Eval. of Active Flow Control Approaches

Notes: 1) All level I milestones are GPRA.

2) PCA milestones are denoted by ☆ (circled)

September 28, 1999
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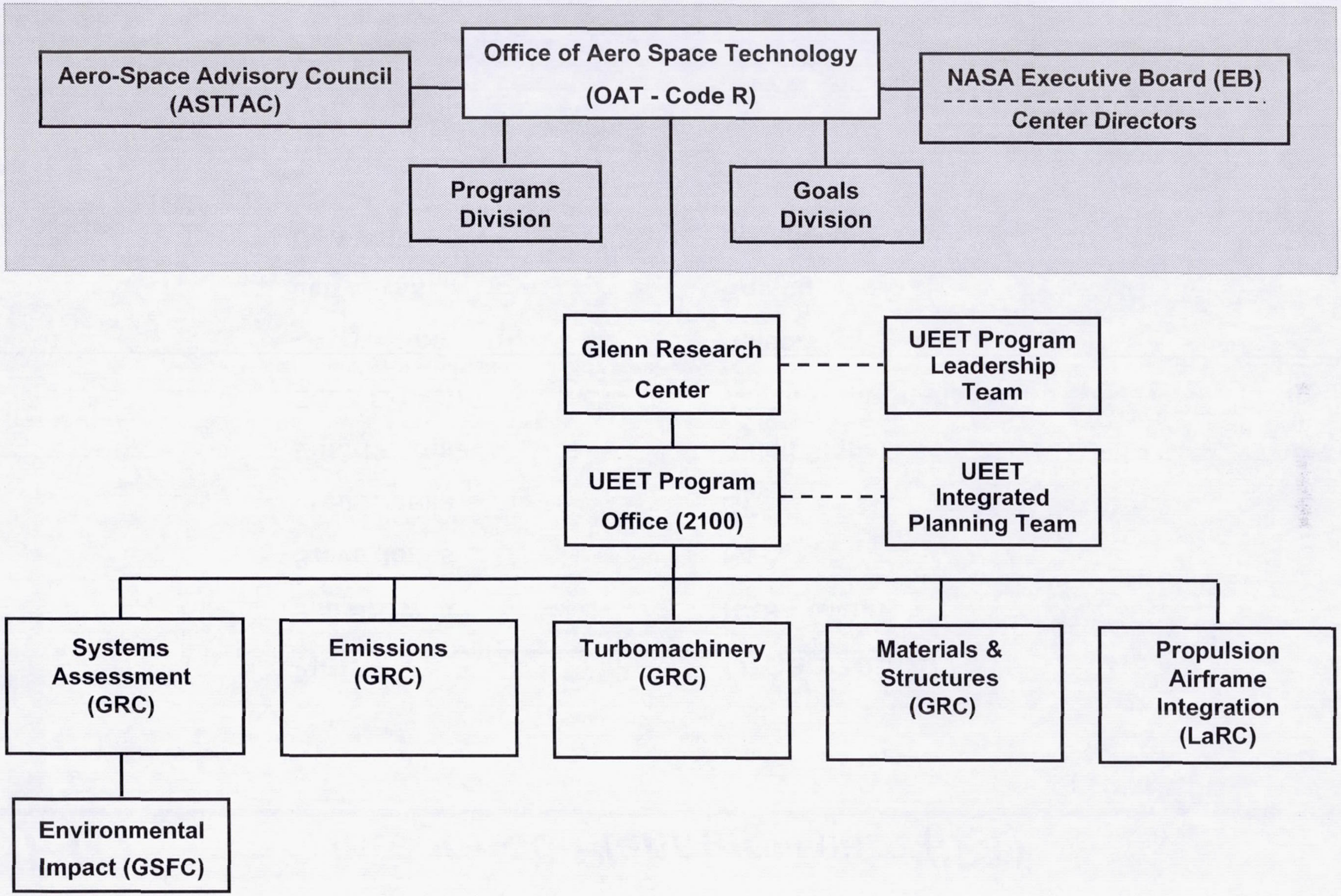
UEET

Resource Requirements
Financial

($M)	FY00	FY01	FY02	FY03	FY04	TOTAL
Gross R&D	50.00	50.00	50.00	50.00	50.00	250.00
Net R&D	39.78	40.34	40.57	40.52	40.46	201.67
1.0 Systems Assessment	2.40	3.10	3.30	3.20	3.20	15.20
2.0 Emissions Reduction	13.60	11.44	10.96	9.84	8.56	54.40
3.0 Highly Loaded Turbomachinery	11.40	9.50	11.10	12.90	14.10	59.00
4.0 Materials & Structures for High Performance	9.68	12.20	10.91	10.18	10.20	53.17
5.0 Propulsion Airframe Integration	2.20	3.60	3.80	3.90	3.90	17.40
6.0 Program Management	0.50	0.50	0.50	0.50	0.50	2.50

Industry Contributions ($M)	8.60	6.60	9.45	11.35	9.30	45.30

UEET Program Organization Structure



NASA/CP—2000-210472/VOL1

UEET *Integrated Planning Team (IPT)*

Name	Organization
Joe Shaw	NASA Glenn
Steve Jones	P&W
Fred Krause	GE
Vinod Nangia	Allied Signal
Scott Cruzen	Williams International
Gerry Brines	Allison
Jeff Lewis	Boeing
Don Williams	Lockheed-Martin

UEET Program Management Team

Name	Organization		Responsibility
Joe Shaw	UEET Program Office	GRC 2100	Program Manager
Bob Plencner	High-Speed Systems Office	GRC 2300	Systems Assessment Project Manager (1.0)
John Rohde	Subsonic Systems Office	GRC 2200	Emissions Project Manager (2.0)
Kaz Civinskas	Subsonic Systems Office	GRC 2200	Turbomachinery Project Manager (3.0)
Ajay Misra	High-Speed Systems Office	GRC 2300	Materials and Structures Project Manager (4.0)
Jim Pittman	Aero Performing Center Management Office	LaRC	Propulsion Airframe Project Manager (5.0)

UEET

Appendix ——>

UEET

Overview
Systems Integration & Assessment (1.0)

Goals

- **Fuel Burn and CO_2 Emissions 8-15 % Reduction**
- **NOx Emissions 70 % Reduction in LTO**

Objectives

- Guide Development of UEET Technologies
- Propulsion System Definition / Integration / Simulation / Assessment
- Environmental Modeling/Assessment

Tech Challenges

- Multiple Vehicle Platforms
- Integrated System Technology Trades and Optimum cycles not established
- Rollup of UEET Technologies to Fleet Impacts
- Undefined geometry for 3_D Simulation
- Complex component interactions not understood
- Reduction of development time & systems testing
- Chemistry and Particle Effects not included in the current Global model
- Complex interactions across tropopause not well understood
- Particle microphysics not well understood

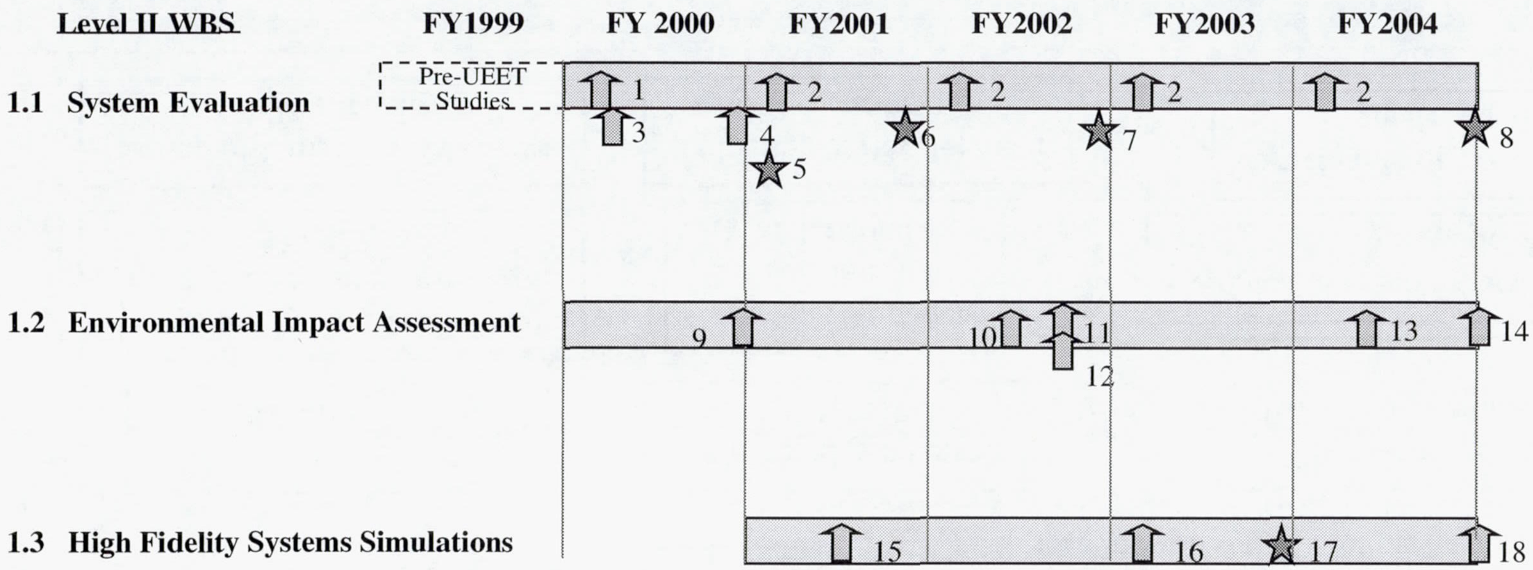
Approaches

- Early Sensitivity Studies
- Technology Trade Studies
- High Fidelity System Simulations
- Environmental Impact Assessments
- Technology Impact Assessments

- ◆ Decision Point
- ☆ Level I Milestone
- ⇧ Level II Milestone

UEET Level I and II Milestone Schedule

Systems Integration & Assessment (1.0)



Outputs

- Baseline A/C & Engines
- Propulsion/Mission Sensitivities
- Concept A/C & Engine Definition
- Annual Metric Assessments
- Characterization of Exhaust Products
- Understanding of Atmospheric Impact
- Understanding of Health Impact (Supersonic)
- Conceptual Mechanical Design
- Component Aero/Thermo Interaction

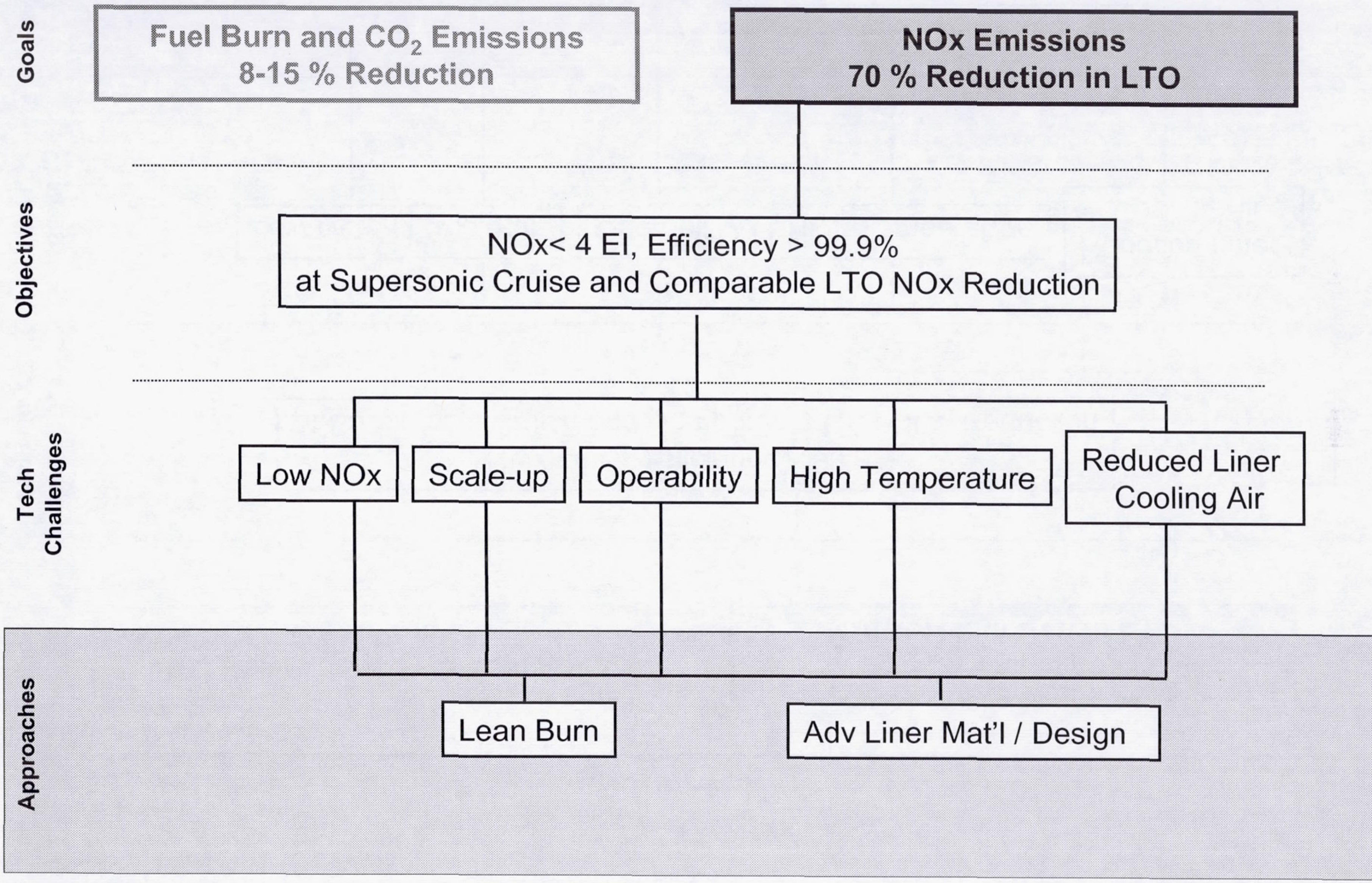
<u>Milestones</u> (*=Level 1)

1. Metric Assessment Process Defined
2. Annual Metrics Assessments
3. Baseline propulsion and airframe tech configs with supporting gross sensitivities (including NOx/CO_2)
4. Preliminary technology trade studies complete
*5. Preliminary Technology Benefits Assessment complete
*6. Propulsion Conceptual Definition
*7. Interim Tech Assessment
*8. Final Technology Assessment
9. Baseline Environmental Impact Assessment
10. Mid-point Emissions Assessment
11. Mid-point Atmospheric Assessment
12. EPA Health Risk Assessment Framework
13. Final Emissions Assessment
14. Final Atmospheric Assessment
15. Selection of system(s) for detailed simulation
16. Conceptual Mechanical Aerodynamic and Thermal Designs
*17. Initial High Fidelity System Simulation (Numeric test cell)
18. Assessment of Numeric Test Cell on Development Time

UEET

Overview
Supersonic

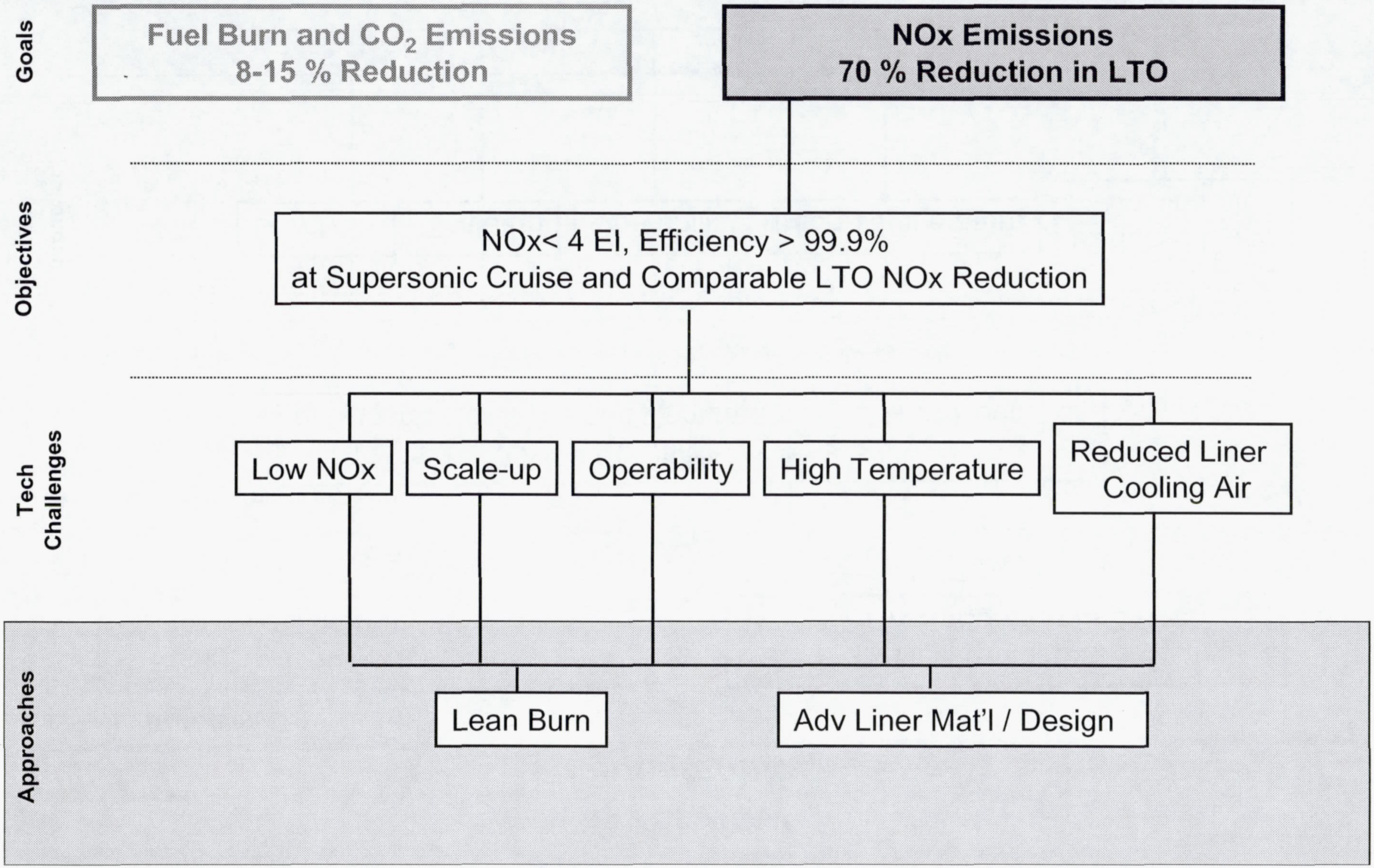
Emissions Reduction (2.0)



Overview
Supersonic

UEET

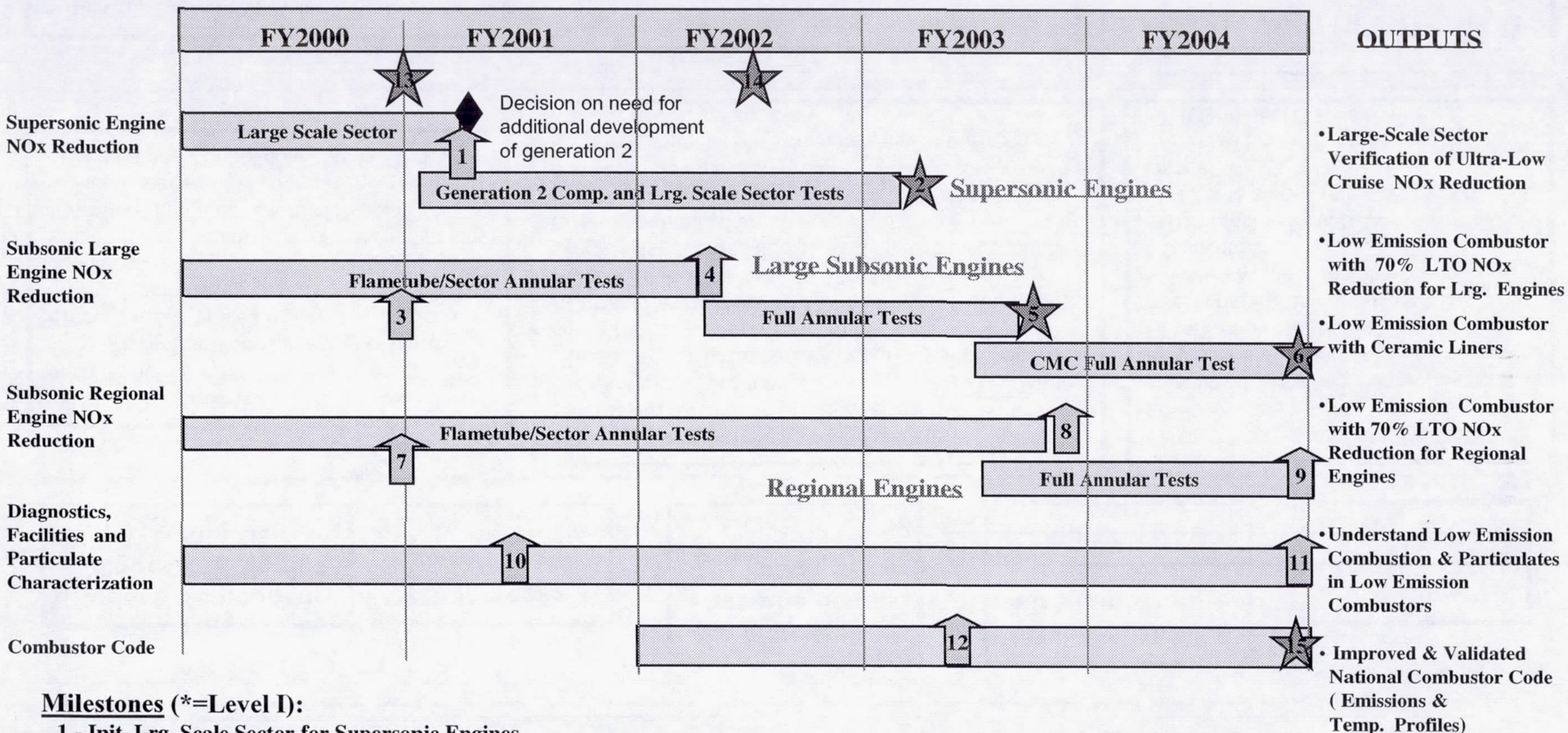
Emissions Reduction (2.0)



◆ Decision Point
★ Level I Milestone
⇧ Level II Milestone

UEET Level I and II Milestone Schedule

Emissions Reduction (2.0)



Milestones (*=Level I):

1 - Init. Lrg. Scale Sector for Supersonic Engines
*2 - Lrg. Scale Sector Verification of Ultra-Low Cruise NOx Combustor
3 - Demo. of 70% LTO Nox Reduction in Flametube for Large Engines
4 - Demo. of 70% LTO NOx Reduction in a Sector Rig for Large Engines
*5 - Demo. of 70% LTO NOx Reduction in a Full Annular Combustor Rig for Large Engines
*6 - Demo. of 2400°F Ceramic Liner in Full Annular Low Emission Combustor
7 - Demo. of 70% LTO Nox Reduction in Flametube for Regional Engines
8 - Demo. of 70% LTO Nox Reduction in Sector for Regional Engines
9 - Demo. of 70% LTO NOx Reduction in a Full Annular Combustor Rig for Regional Engines
10 - Complete Second Leg of Advanced Subsonic Combustion Rig
11 - Establish Understanding of Particulate with Advanced PAGEMS
12 - Init. Assessment of Subsonic Combustor Concepts with the National Combustor Code.
*13 - 70% LTO NOx Reduction Demonstrated in Flametube
*14 - 70% LTO NOx Reduction Demonstrated in Sector Rig
*15 - Physics Based Prediction Codes Validated (Combustors)

UEET Overview

Highly-Loaded Turbomachinery (3.0)

Goals

Fuel Burn and CO_2 Emissions 8-15 % Reduction	NOx Emissions 70 % Reduction in LTO

Objectives

- Reduce Component Weight -20%, Engine Weight -5%
- Increase Efficiency by 1% to 2%
- Increase Average Stage Loading +50%
- Increase Turbine Inlet Temperature +400°F at Commercial Life
- Reduce Cooling Flow by 25%

Tech Challenges

• Large fan stage rotor-stator spacing dictated by noise • High risk for structural integrity of blades • Flow through blades limited by thickness • Aero design needs to satisfy all operating conditions • Minimize cost/complexity of new technology • Minimize fan/stator interaction noise with reduced spacing • Execute flow control concepts in 3D design	• Strong interaction of shock and viscous layers • Increased diffusion in blade rows leads to higher losses without flow control • Goals require turbomachinery performance beyond current "design space" • Current design rules lead to low aspect ratios which will tend to increase weight & losses • Higher aspect ratio at high loading levels susceptible to aeromechanical problems • Higher loading limited by flow breakdown near endwalls and on blading • Stability impacted by strong interaction between leakage flows and shocks	• Higher coolant temperature at 55:1 OPR • Accurate prediction of internal and external heat loads • Prediction of localized heat transfer effects particularly at edges & tips • Unsteady effects on film-cooling effectiveness • High Mach effects between HP and LP turbine stages (shock & mixing losses) • Adverse flow impact of high-flare interstage duct & LP geometries

Approaches

• Trailing edge blowing to fill wakes and allow close coupling • Flow management through self-pumping within blade (Aspirated airfoils) • Endwall and tip leakage flow management • 3D viscous inverse design	• Physics-based modeling of flow control concepts • 3D blading (sweep, lean, scallop, etc) • Multistage 3D viscous CFD (steady & unsteady) • Active/passive stability control • Rig tests of flow control concepts in single-stage, multistage, and subsystem configurations	• Physics-based fluid/structural modeling for 3D heat transfer analysis of advanced cooling • Aspirated LP airfoils • Flow control for HP/LP turbine interstage ducting • Rig test of close coupled HP/LP turbine system in dual-spool facility

Decision Point
Level I Milestone
Level II Milestone

UEET Level II Milestone Schedule

Highly-Loaded Turbomachinery (3.0)

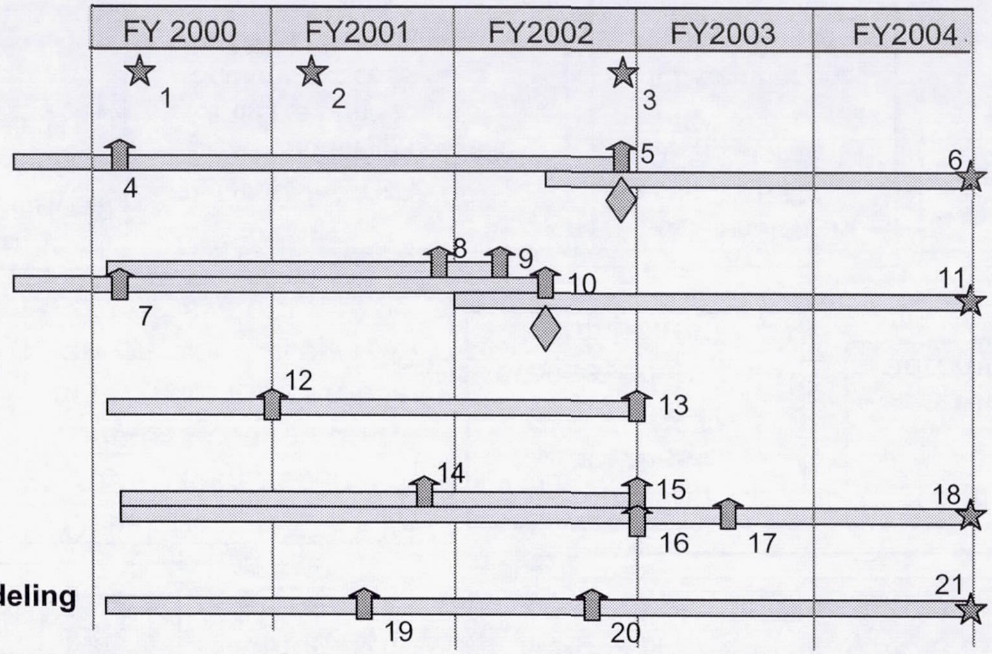
3.1 Reduced Weight Fan

3.2 Multistage Compressors and Fans

3.3 High Efficiency Reduced Cooling HPT

3.4 Ultra-High-Loaded HPT/LPT System

3.5 Flow Physics Based Modeling



OUTPUTS

- Baseline Performance Database
- Blown IGV Performance
- R-S Close Coupling
- Demonstration of Flow Control/Aspiration Concepts in Single-Stages
- Ultra-effective cooling concept
- 55 OPR, 3100Fw/25% less coolant
- Demo. Of Flow Control Concept for LPT
- Multistage/Subsystem Demo. of Ultra-High Aero Loading
- Demo. of Ultra-High Loaded HPT/LPT Subsystem
- 1/3 fewer stages
- Physics-Based Prediction Codes

Milestones (*=Level 1):

* 1. Flow Control Concept Selected - Fan, Compressor
* 2. Flow Control Concept Selected - Turbine
* 3. Flow Control POC's
4. LPR Fan Flow Control Concept Defined
5. LPR T.E. Ejection Concept Rig Test (Low Tip Speed Fan)
* 6. Flow Control Validation Test
7. Compressor Flow Control/Aspiration Concept Defined
8. High-Loaded Multistage Performance Baseline Established (HSR 2-Stage)
9. Performance w/Blown IGV T.E. (HSR 2-Stage)
10. Highly-Loaded Flow-Controlled/Aspirated Single-Stage Compressor Test
*11. Multistage Highly-Loaded Rig Test
12. Cooling concept design(s)
13. Rig test evaluation of ultra-effective cooling concept
14. Application to ultra-high-loaded, high-efficiency blading
15. Rig test of ultra-high-loaded stage
16. Counter-rotating dual-spool rig operational
17. Transition duct flow control concept selected
*18. Rig test of highly-loaded, closely-coupled HP/LP turbine stages
19. Flow control models for design developed
20. Completed validated simplified model for particulates
21. Validated Physics-Based Prediction Capability for Design of Ultra-High Loaded Turbomachinery

UEET

Overview (1 of 2)

Materials & Structures for High Performance (4.0)

Goals

- **Fuel Burn and CO_2 Emissions 8-15 % Reduction**
- NOx Emissions 70 % Reduction in LTO

Objectives

- Long-life disk and airfoil materials for 3100°F turbine rotor inlet temp. and pressure ratio > 55:1
- CMC vane for 3100°F turbine rotor inlet temperature
- Weight reduction through extending use temperature range of PMC's and developing innovative lightweight materials and structural concepts for engine structures

Tech Challenges

- Demonstrating properties at 1400°F in scaled up disk forgings
- Developing TBC's with 300° F increase in •T across coating and demonstrating durability of combined alloy/TBC system
- Achieving properties at 550°F in RTM processed engine component
- Reduction in weight of supersonic exhaust nozzle without sacrificing aerodynamic performance

Approaches

- Test and characterize HSR-EPM disk alloy to (1) establish use temperature limit, (2) verify projected properties in scaled up forgings, (3) verify life prediction models, (4) demonstrate properties in subcomponents
- Alternate heat treatment process for increasing temperature capability of HSR-EPM disk alloy

- Develop adv. TBC
  - Low conductive ceramic
  - Optimize bondcoat
  - Scaleup process
- Use EPM blade alloy
  - Est. temp. limit
  - Reduce bondcoat reaction
- Rig test coated blades

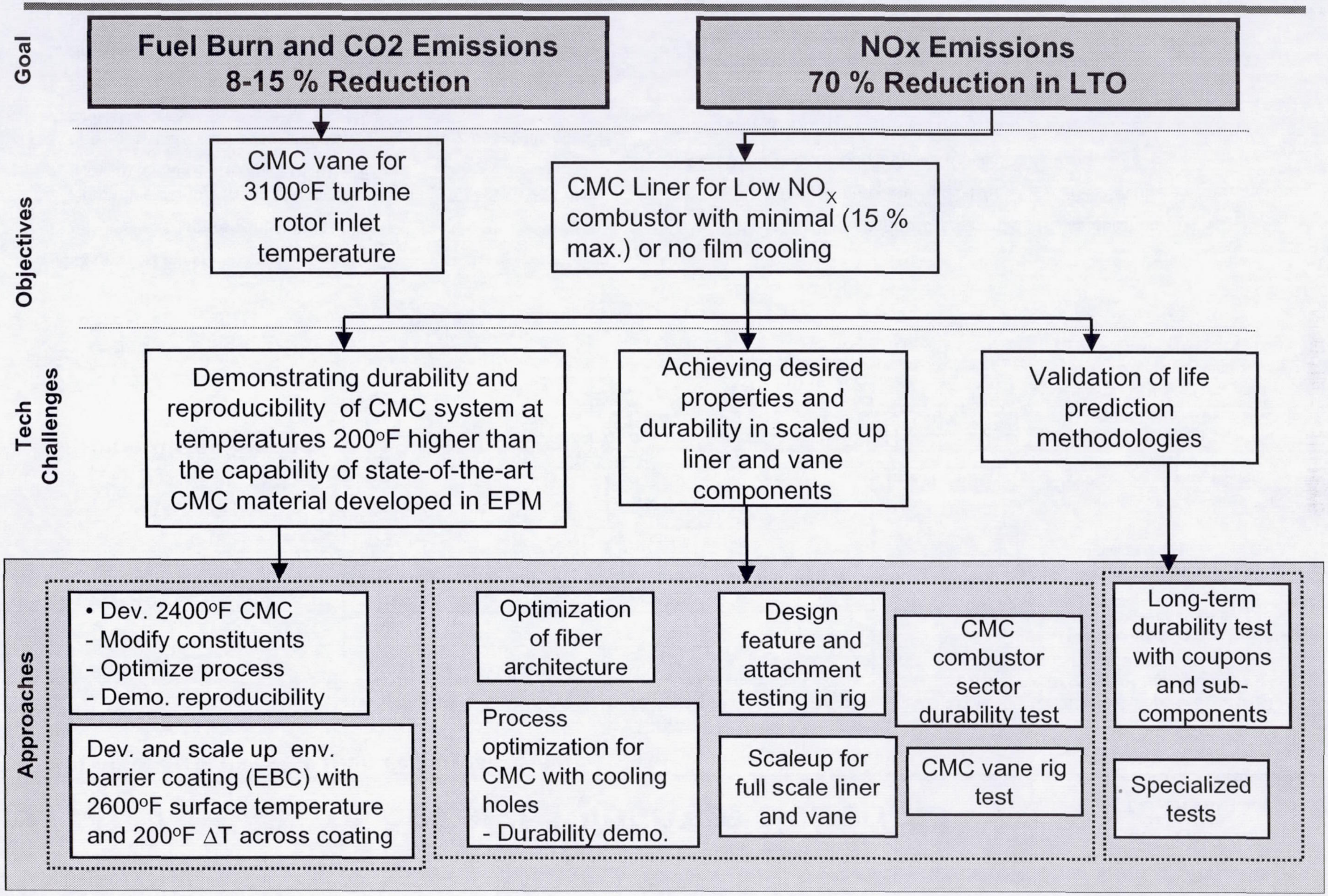
- Scale up solvent-assisted RTM process for 550°F PMC
- Sub-component testing
- Fabricate full scale engine component
- Engine test

- CMC mixer
- Lightweight concepts
  - TiAl honeycomb
  - Engineered superalloy structure
  - Aerodynamic concepts
- Subcomponent test

Overview (2 of 2)

UEET

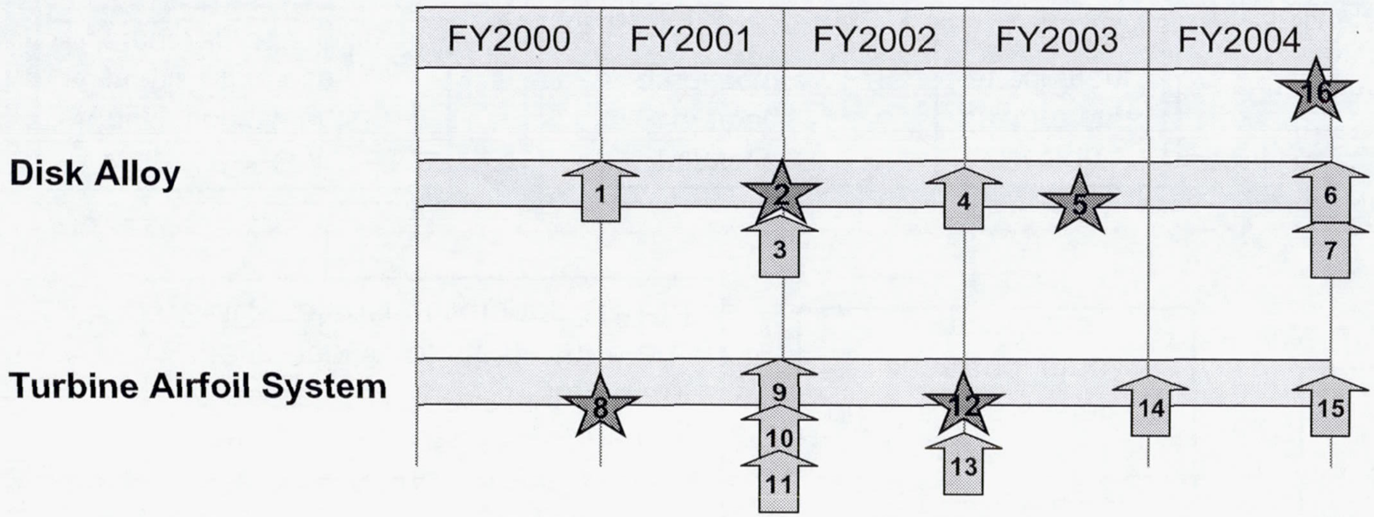
Materials & Structures for High Performance (4.0)



UEET Level II Milestone Schedule

◆ Decision Point
☆ Level I Milestone
⇧ Level II Milestone

Materials & Structures for High Performance (4.0)



Outputs

- Demo'd properties in scaled-up HSR-EPM disk alloy at 1350°F
- Processing capability for achieving properties at 1400°F
- Verified probabilistic life prediction model

- Low conductive ceramic TBC composition & process for coating blades
- Optimized alloy/TBC system for 3100°F turbine inlet temperature
- Alloy/TBC combination demo'd in rig tests

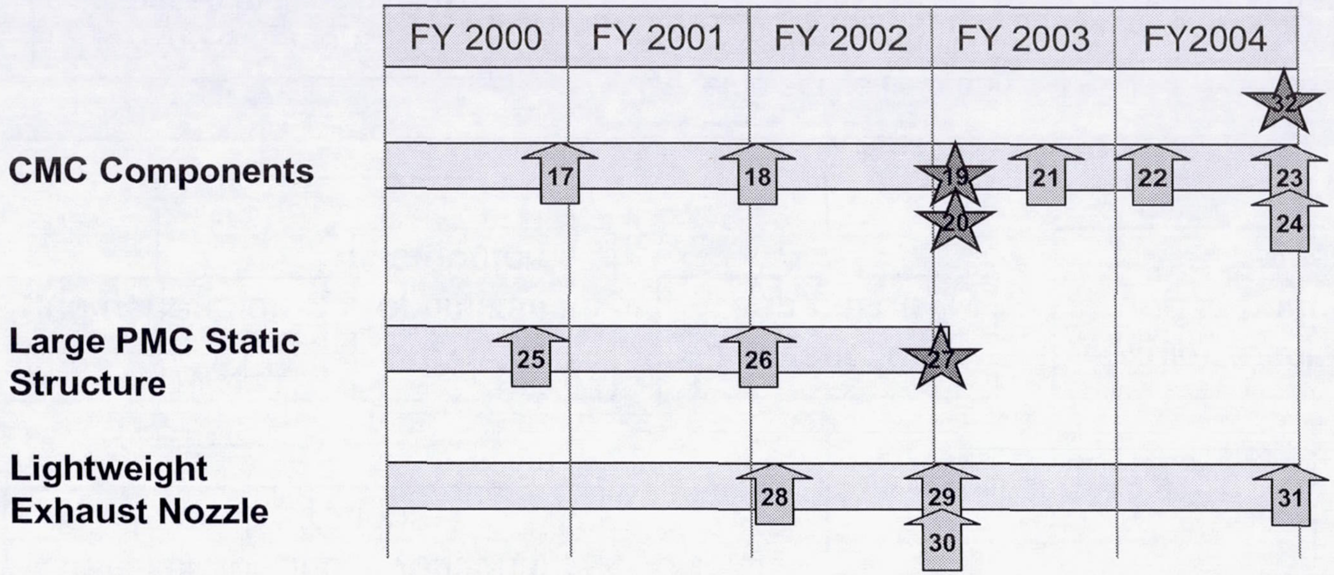
Milestones (*=Level I)

1. Alloy selected for regional engines
* 2. Properties demonstrated in scaled-up forgings for HSR-EPM disk alloy in temperature range of 1350°F
3. Feasibility established for increasing temperature capability of HSR-EPM disk alloy
4. Properties demonstrated in scaled up disk alloy for regional engines
* 5. Process selected for 1400°F disk
6. Properties demonstrated in 1400°F disk
7. Probabilistic disk life prediction model validated
* 8. Low conductive ceramic TBC concepts selected
9. Feasibility of low conductive ceramic TBC established
10. Upper temperature limit established for HSR-EPM blade alloy
11. Bondcoat composition and process optimized
*12. Low conductive ceramic TBC system and process selected
13. Process optimized for preventing alloy-bondcoat interaction
14. Low conductive ceramic TBC process scaled up
15. Rig testing of coated blades complete
16. High Temp. Materials Capabilities Demo. (same as 32 on next chart)

◆ Decision Point
★ Level I Milestone
⇧ Level II Milestone

UEET Level II Milestone Schedule

Materials & Structures for High Performance (4.0)



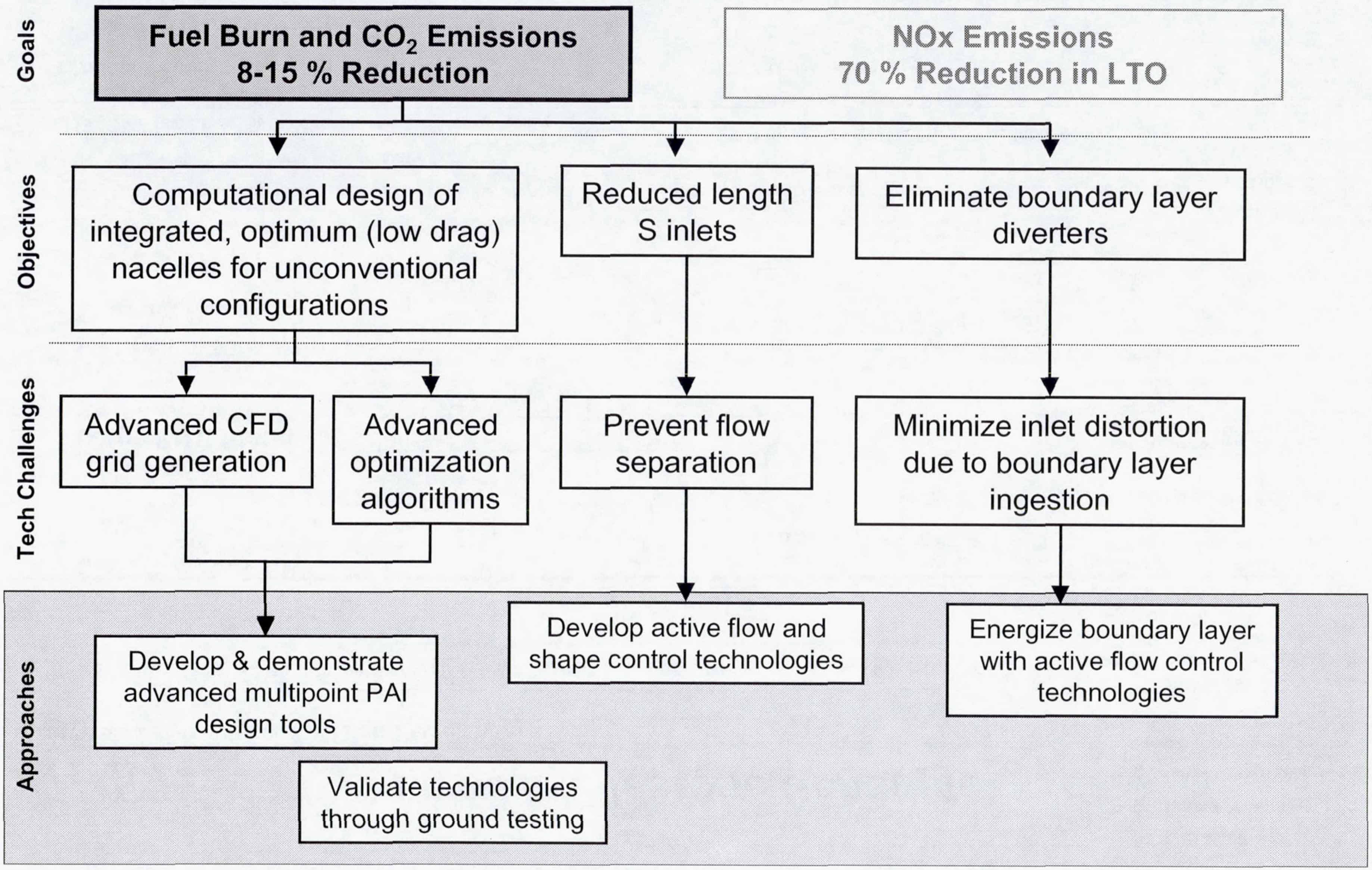
Outputs

- 2400°F CMC material and 2600°F environmental barrier coating (EBC)
- Verified liner/vane design
- 200 hr. sector liner and vane rig test and 1000 hr. design feature test in rigs
- Verified life prediction models
- Demo'd processing capabiity for fabricating 550°F PMC engine components
- Verified concepts for decreasing weight of supersonic exhaust nozzle

Milestones (*=Level I)

17. Upper temperature limit of HSR-EPM CMC established
18. CMC system developed for combustor liner
*19. CMC combustor liner subcomponent/sector durability demonstrated in rig test for 200 hr.
*20. CMC system developed for turbine vane
21. CMC process scaled up for full scale annular rig test
22. Design features demonstrated for turbine vane
23. CMC vane rig test complete
24. CMC liner subcomponent durability demonstrated for 1000 hr. in rig test
25. PMC resin and process selected for engine component fabrication
26. Engine test ready 550 °F PMC fabrication complete
*27. Engine test complete with 550 °F PMC structure
28. CMC mixer fabrication demonstrated
29. CMC mixer test complete
30. Lightweight materials/structural/aerodynamic concept selected
31. Subcomponent test with adv. lightweight concept complete
32. High Temp. Materials Capabilities Demo (same as 16 on previous chart)

UEET Overview



◊ Decision Point
★ Level I Milestone
⇧ Level II Milestone

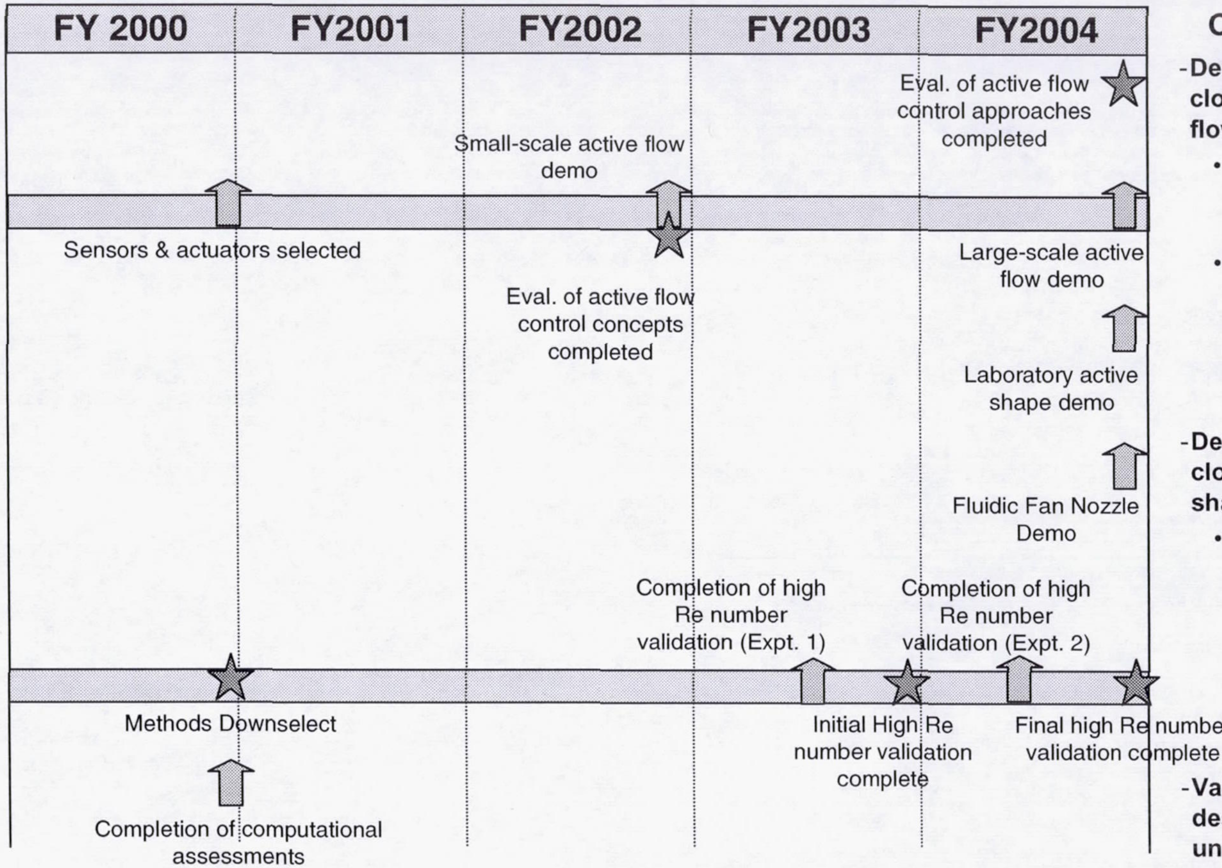
UEET Level 2 Milestone Schedule

Smart Nacelle Technologies

- **Active Flow Control Inlet**
- **Active Shape Control Inlet**
- **Fluidic Nozzle Area Control**
- **Research methods**

Advanced PAI Concepts

- **Advanced methods**
- **Unconventional Configurations**
- **Wind tunnel validation**



OUTPUTS

- **Demonstration of closed loop active flow control to:**
  - **Energize airframe boundary layer**
  - **Prevent flow separation**
- **Demonstration of closed loop active shape control to:**
  - **Prevent flow separation**
- **Validated, advanced design tools for unconventional configurations**

WELCOME TO UNITED AIRLINES

Sherry Soditus
United Airlines
San Francisco, California

UNITED AIRLINES

Welcome to United Airlines

- Current Fleet Of 577 Aircraft
  - Mix Of DC10, 727, 737, 747, 757, 767, 777, A320, A319
- Average Age Of The Fleet Is 10 Years
- 2260 Flights / Day; 230,000 Passengers / Day
- 81.9 Million Passengers Per Year

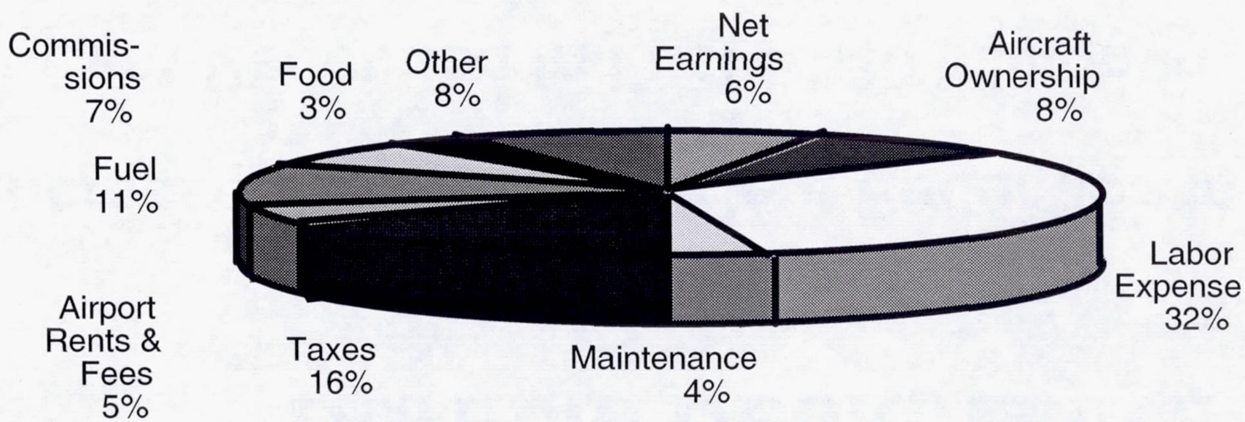
UNITED AIRLINES

The Bottom Line

- $$$

UNITED AIRLINES

Distribution of One U.S. Passenger Dollar



UNITED AIRLINES

The Need For Effective And Durable Designs

- **Increase η By 1.5% = 1 Cent Reduction In Fuel**
- **1 Cent Reduction In Fuel = $30 Million In Savings / Year**
- **Increase Durability = Reduction In Premature Removals And Reduced Maintenance Cost**

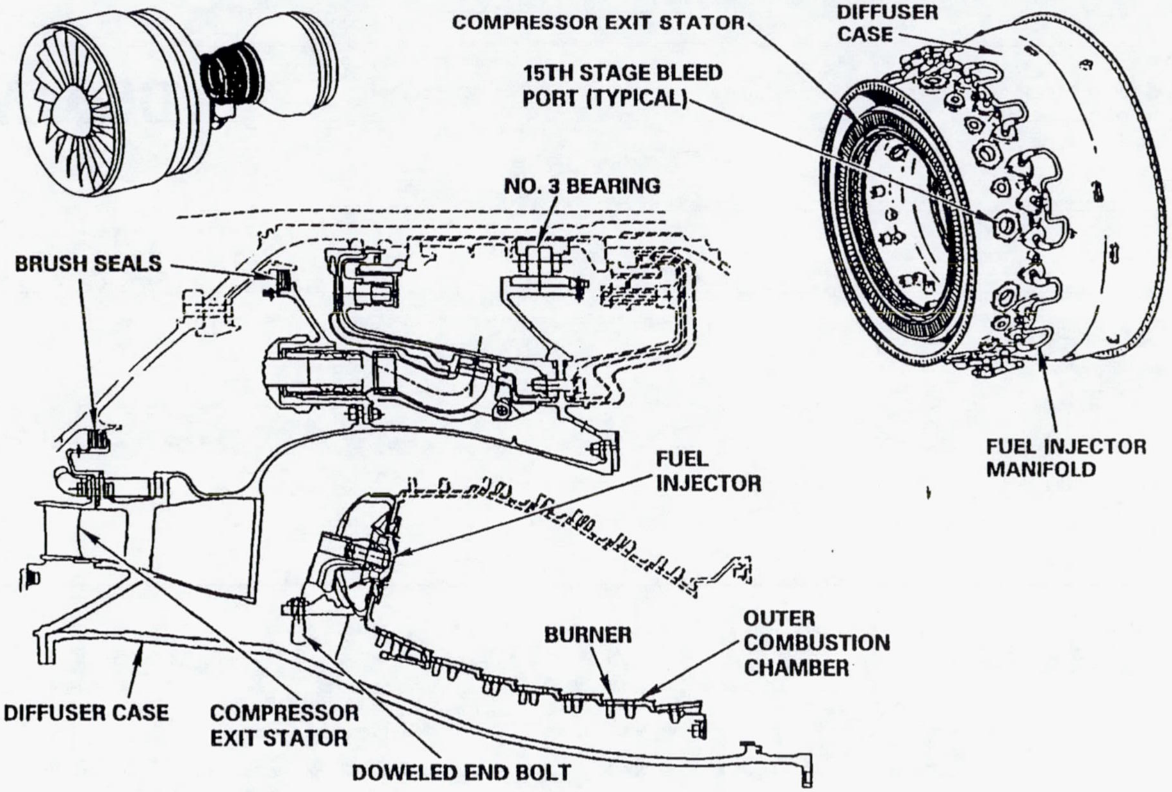
UNITED AIRLINES

Brush Seals Are The Wave Of The Future

- PW4000-3
- PW4077
- PW4090
- V2500

UNITED AIRLINES

Diffuser And Combuster Brush Seals

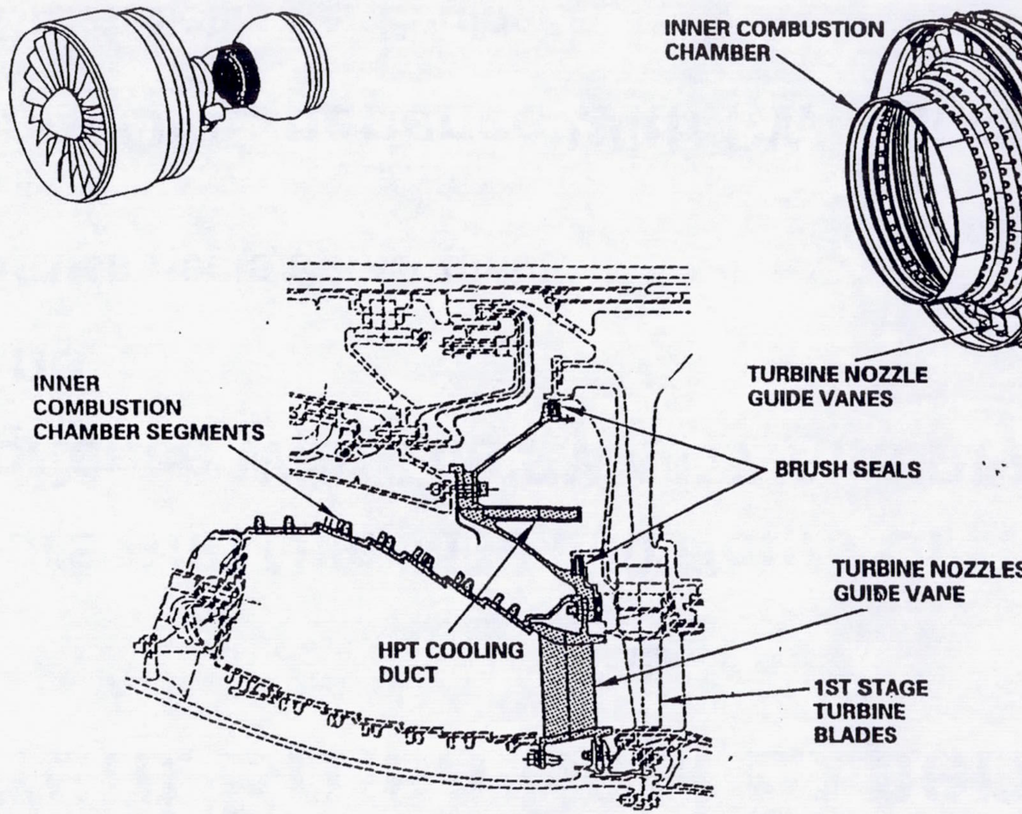


DIFFUSER AND COMBUSTOR

FOR TRAINING PURPOSES ONLY

United Airlines

HPT Brush Seals



FOR TRAINING PURPOSES ONLY

TURBINE NOZZLE

UNITED AIRLINES

Current Brush Seal Experience

- 4 Years And Over 600,000 Hours Of Experience With The PW4077 And PW4090 Engine
  - 4 Brush Seals Per Engine
- 3 Years Of Experience With PW4000-3
  - 3 Brush Seals Per Engine
- At Overhaul Experience Has Shown
  - 100% Replacement on PW4077/PW4090
  - 50% Replacement on PW4000-3

UNITED AIRLINES

Estimated Expenditure For Brush Seals In Year 2000

Engine	Module	Est. No. Modules Overhauled In 2000	Brush Seal $ / Module	Annual Cost
PW4000-3	Diffuser Case	26	31,020	1,613,040
	HPT	27.5	8,415	462,825
				2,075,865
PW4077	Diffuser Case	10	62,040	620,400
	HPT	13	70,860	921,180
				1,541,220
PW4090	Diffuser Case	17	72,610	1,234,370
	HPT	19	87,900	1,670,100
				2,904,470

TOTAL ESTIMATE COST FOR BRUSH SEALS IN YEAR 2000

$6.5 MILLION

UNITED AIRLINES

Intangible

- **Decrease In TSFC Due To Deterioration**
- **Reduction To HPT Life Due To Improper Cooling And Increased Leakage**

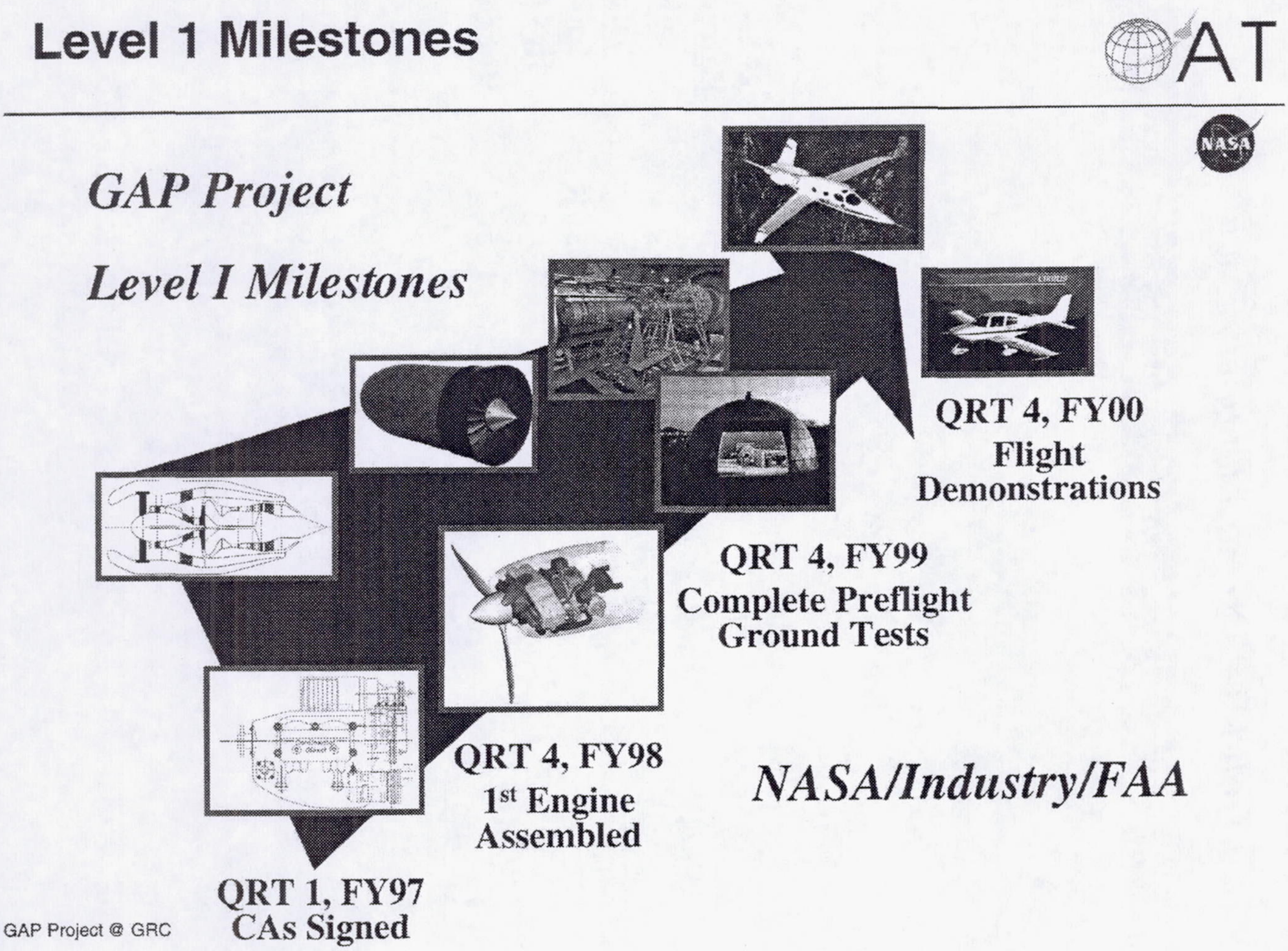
UNITED AIRLINES

Goals

- **Opportunity To Examine Real Life Experience And To Understand The Overall Picture**
- **Opportunity To Make Large Impact On Airline Operating Cost By Reducing**
  - TSFC Deterioration
  - Premature Overhauls
- **Opportunity To Pass Savings Onto Consumer**

GENERAL AVIATION PROPULSION PROGRAM AND BEYOND

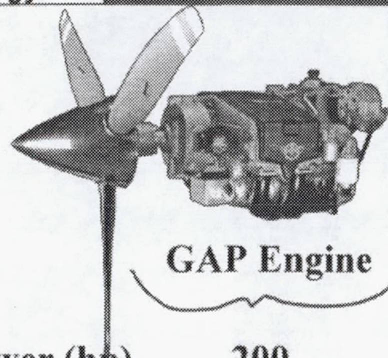
Leo A. Burkardt
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio



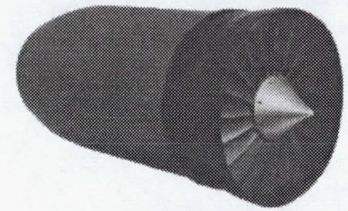
Trend Setting Revolutionary Engines

NASA Office of
Aero-Space Technology

Safe Air Accessibility for Information Age Communities



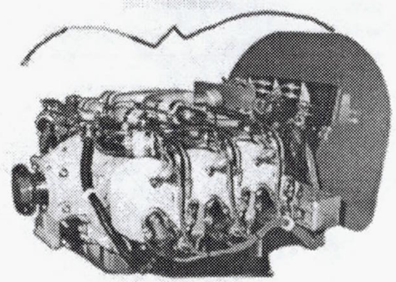
GAP Engine



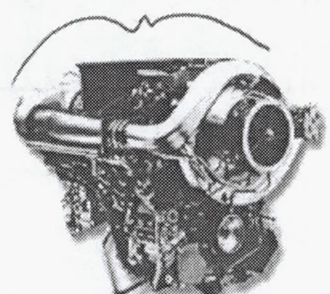
FJX-2

IO 360 ES		GAP Engine
210	Power (hp)	200
420	Weight (lb)*	~ 420
Gasoline	Fuel	Jet
Air	Cooling	Liquid
0.45	bsfc	0.36
$30K	Cost	~ $15K**
1800	TBO (hr)	3000
Noisy & Harsh	Comfort	Quiet & Smooth

Allison 250-B17C		FJX-2
	Thrust (lb)	700
420	Power (hp)	~ 500
195	Weight (lb)	< 100
0.66	bsfc	< 0.5
$230K	Cost	~ $65K**
3500	TBO (hr)	5000
1750	Hot Sec. (hr)	2500



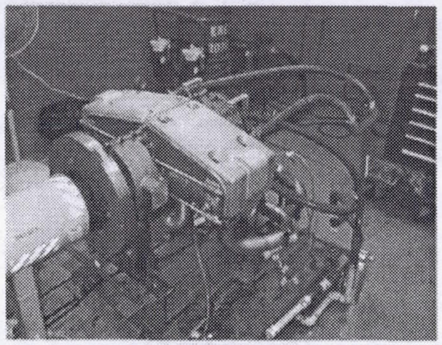
IO 360 ES



Allison 250-B17C
Turboprop

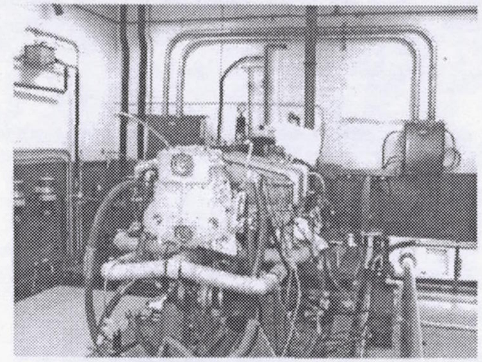
* Installed Weight (Including Fluids)
** Production Rate ~2000/year

Diesel Making Good Progress

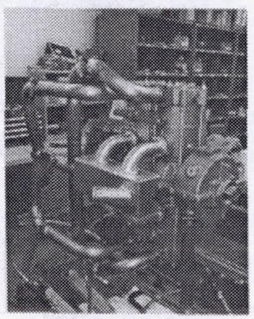


Engine In Test Cell

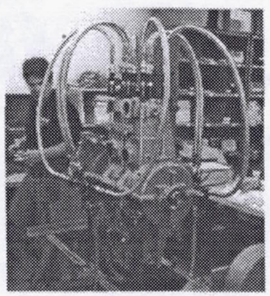
- Component fit and assembly thoroughly assessed and tested
- Development engine testing in progress



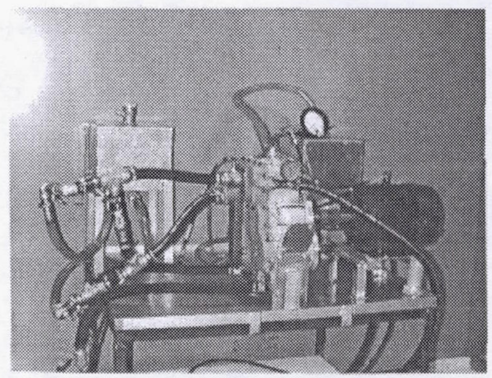
Engine In Test Cell



INTAKE & EXHAUST



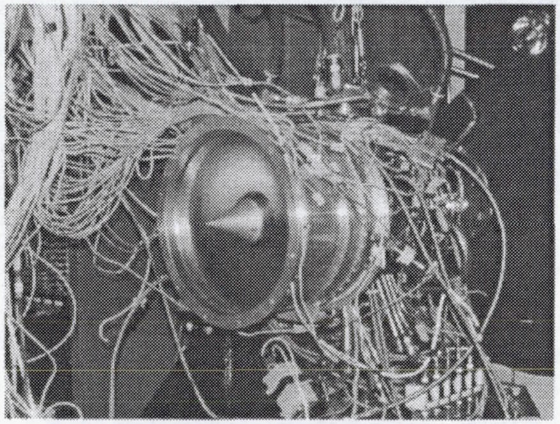
THRU-BOLT TENSIONING



ACCESSORY DRIVE TESTING

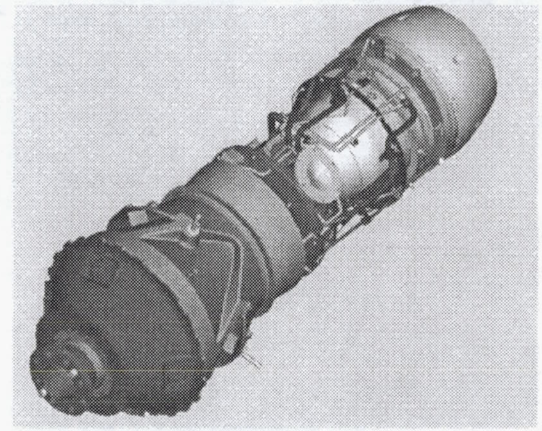
FJX/TSX Making Good Progress

AT

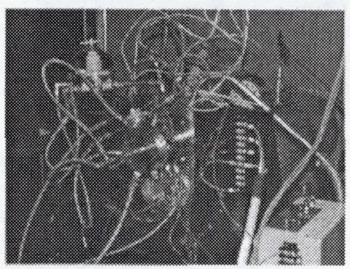


Full Engine
In Test Cell

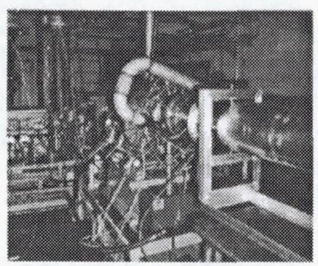
- Key components thoroughly tested in rigs and core engine
- Development engine testing in progress
- TSX-1 gearbox assembly in progress



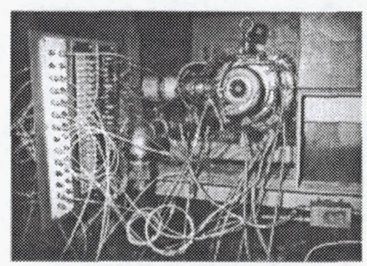
TSX-1



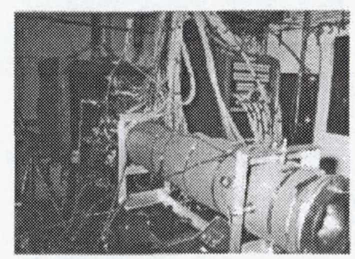
Starter/Alternator



Compressor



Combustor

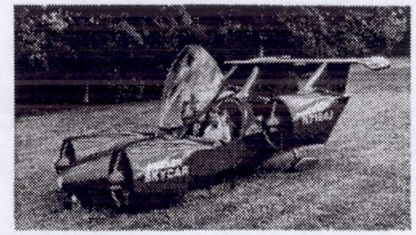


Core Engine

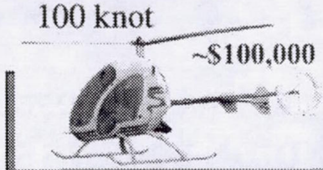
GAP Project @ GRC

SATS 2001

Small Aircraft Propulsion
Technologies For The Future

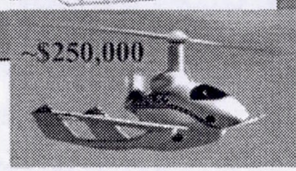


100 knot



~$100,000

~$250,000



250 knot

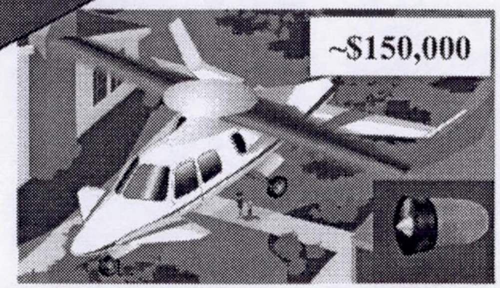
2003

Personal VTOL

"Doorstep to Destination"

Ultra-Safe All-Weather

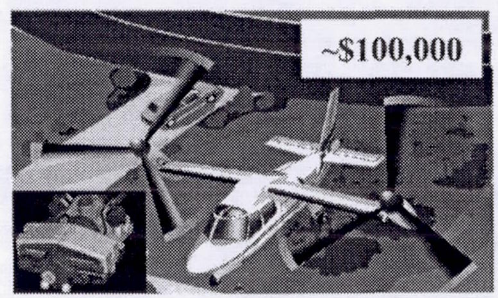
2010



~$150,000

~$25,000

400 knot



~$100,000

~$5,000

200 knot

- Whisper-quiet, ultra-light, low-cost propulsion systems
  - Engines
  - Propellers & Rotors
  - Transmissions with high reduction ratio gearing
- Low-cost ultra-low emissions
- Failsafe, affordable flight/propulsion <u>Supervisor</u>
  - Intelligent - configures & controls aircraft/propulsion system
    - = Pilot guides vehicle, supervisor flies and controls it
    - = Reconfigures systems & advises pilot when malfunction occurs
- Failsafe, low-cost composite structures

SATS VTOL

NASA/CP—2000-210472/VOL1

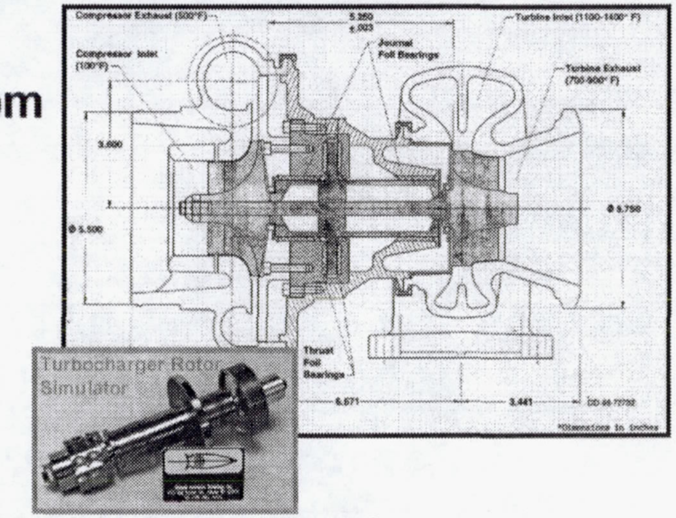
Future Plans: Oil-Free Turbine Engine Project

Relevant Program

Oil-Free Turbocharger Status (Propulsion Base)

Accomplishments:

- **Rotor/bearings tested up to 121,500 rpm**
  (equivalent to 4.4 MDN)
- **Dynamic runout (orbit) < 1.0 mil**
  (5-8 mil typ. conventional oil lube turbo)
- **20 g shock loads**
- **Low Power Loss**
  (Estimated at 2 hp; 10 hp for typ. oil lube turbo)
- **Successful Gas Stand Test**
  (Full-speed, 95,000 rpm & Maximum Turbine Inlet Temperature, 1,200°F)



Remaining Activities:

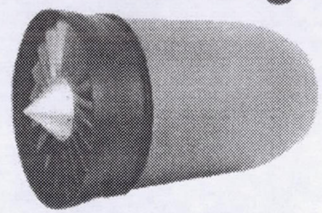
- **Turbocharger performance test on gas stand**
- **Engine performance test**
- **Engine emissions test (particulate)**

Glenn Research Center

PROPULSION SYSTEMS BASE PROGRAM

AT

Oil-Free Turbine Engine Technology Project



- Advance foil bearing design and analysis techniques
  - SOA foil bearing design and analysis is an art
  - Develop analytic capabilities to design and analyze bearings and shaft bearing systems
- Convert FJX-2 to oil-free operation and test engine
  - Develop foil bearing system for FJX-2 turbofan engine
    - > FJX-2 was designed to accommodate foil bearings
  - Incorporate, adapt and prove technologies developed for hot section foil bearings at GRC in turbine engine
  - Prepare for flight demonstration
- Transfer technology and lessons learned to US turbine engine industry
- Develop gear and bearing technologies for low-oil transmission
  - Provide a full scale demonstration of technologies

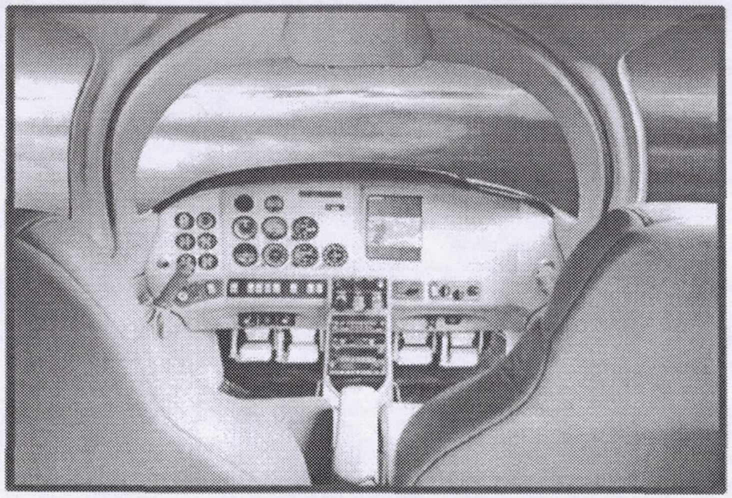

SATS - A Safe, Affordable and Rapid
Intermodal Transportation System

AGATE/GAP Usher In A New State of the Art

NASA Office of Aero-Space Technology

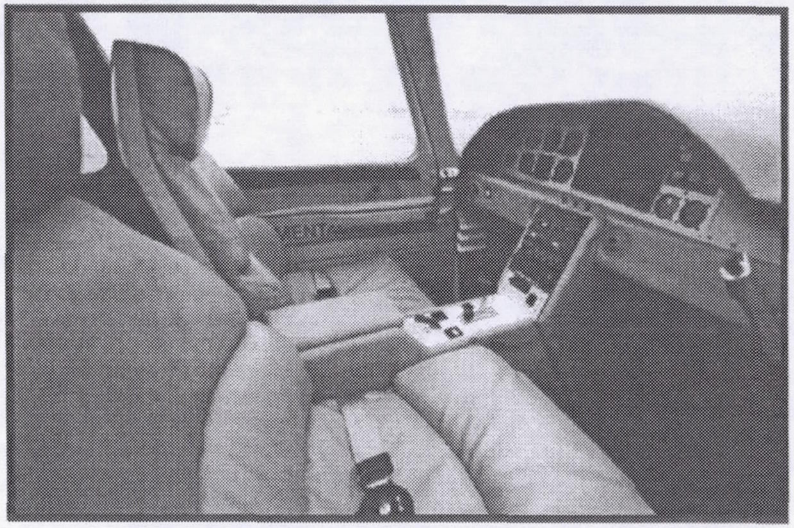
Safe Air Accessibility for Information Age Communities

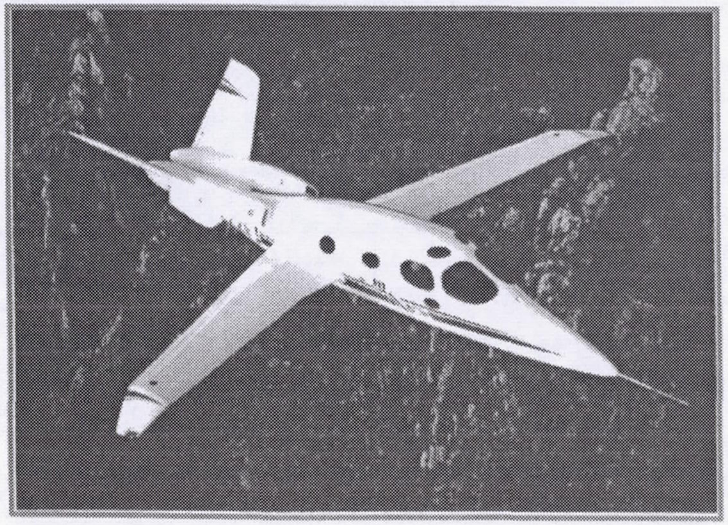
The New Generation Cockpits and Aircraft



Lancair Columbia 300

Cirrus SR-20



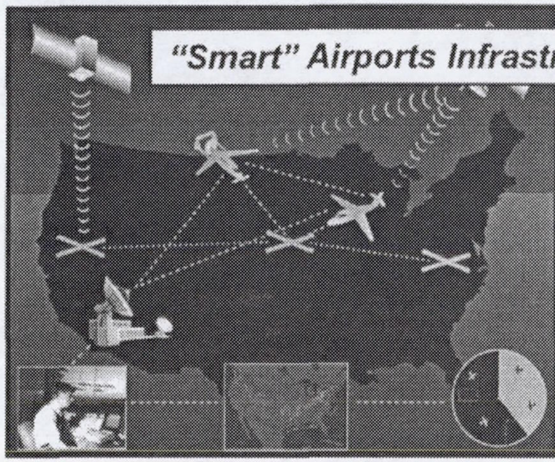


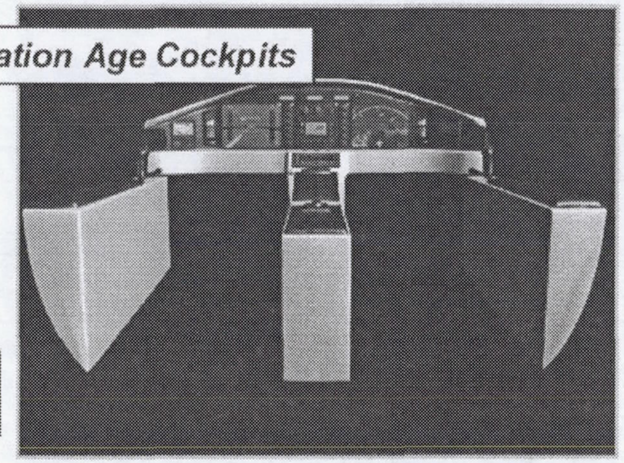
Williams V-Jet

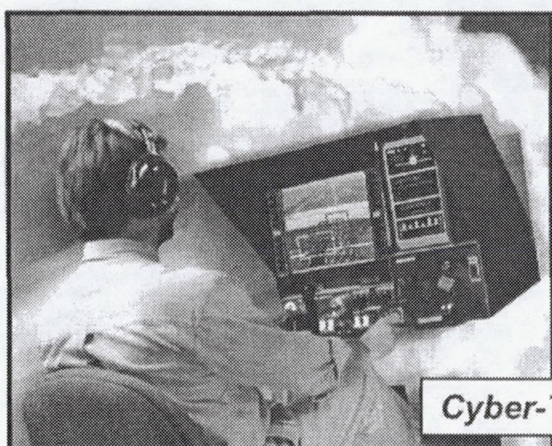
SATS Takes a System Approach to Transportation & Safety

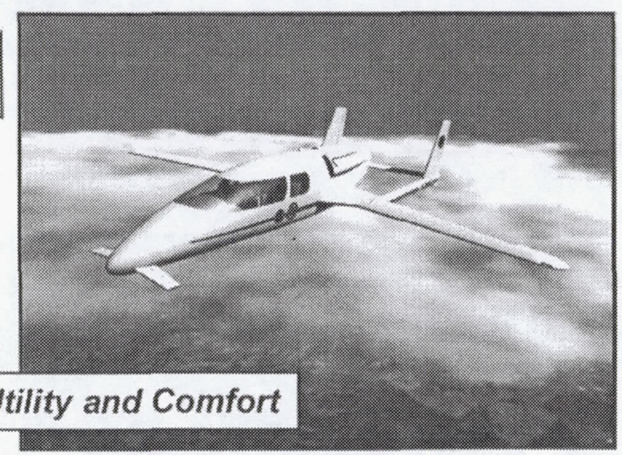
NASA Office of Aero-Space Technology

Safe Air Accessibility for Information Age Communities









Autoflight

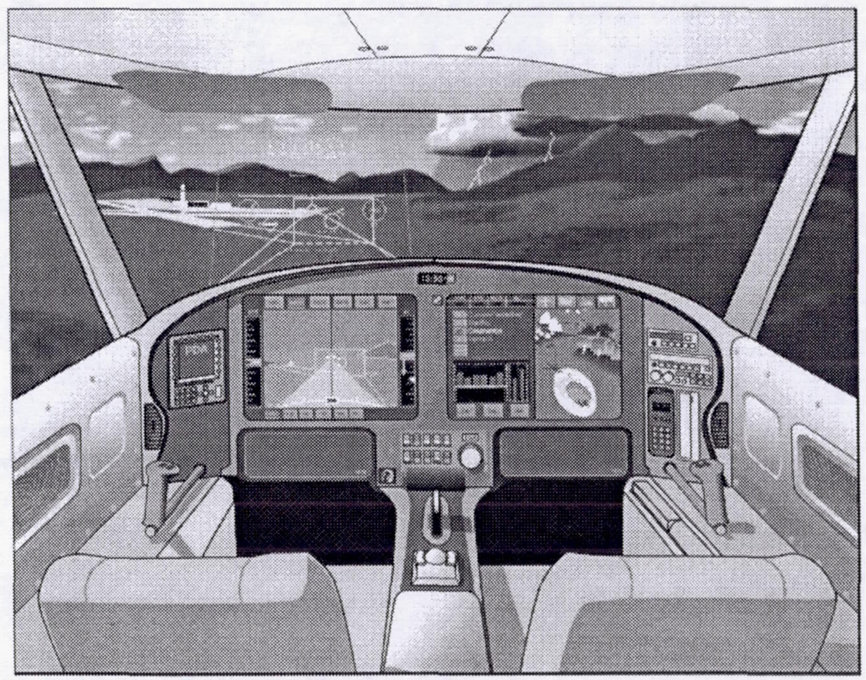
NASA Office of Aero-Space Technology

Safe Air Accessibility for Information Age Communities

Reduce the complexity of aircraft control to car-like simplicity. Single-crew SATS aircraft operators will utilize simplified controls with automated assistance to navigate on virtual skyways. The objective is to achieve commercial aircraft levels of safety and navigational performance. The result will reduce cost and increase mission reliability for both hired-pilot and self-flown operations.

Features:

- **Automatic intelligent controls which limit attitude & altitude excursions, and configures aircraft/propulsion for flight mode**
- **Safe operations by single-crew and lower-time users**
- **Abuse-tolerant controls**
- **Common interface across vehicles**



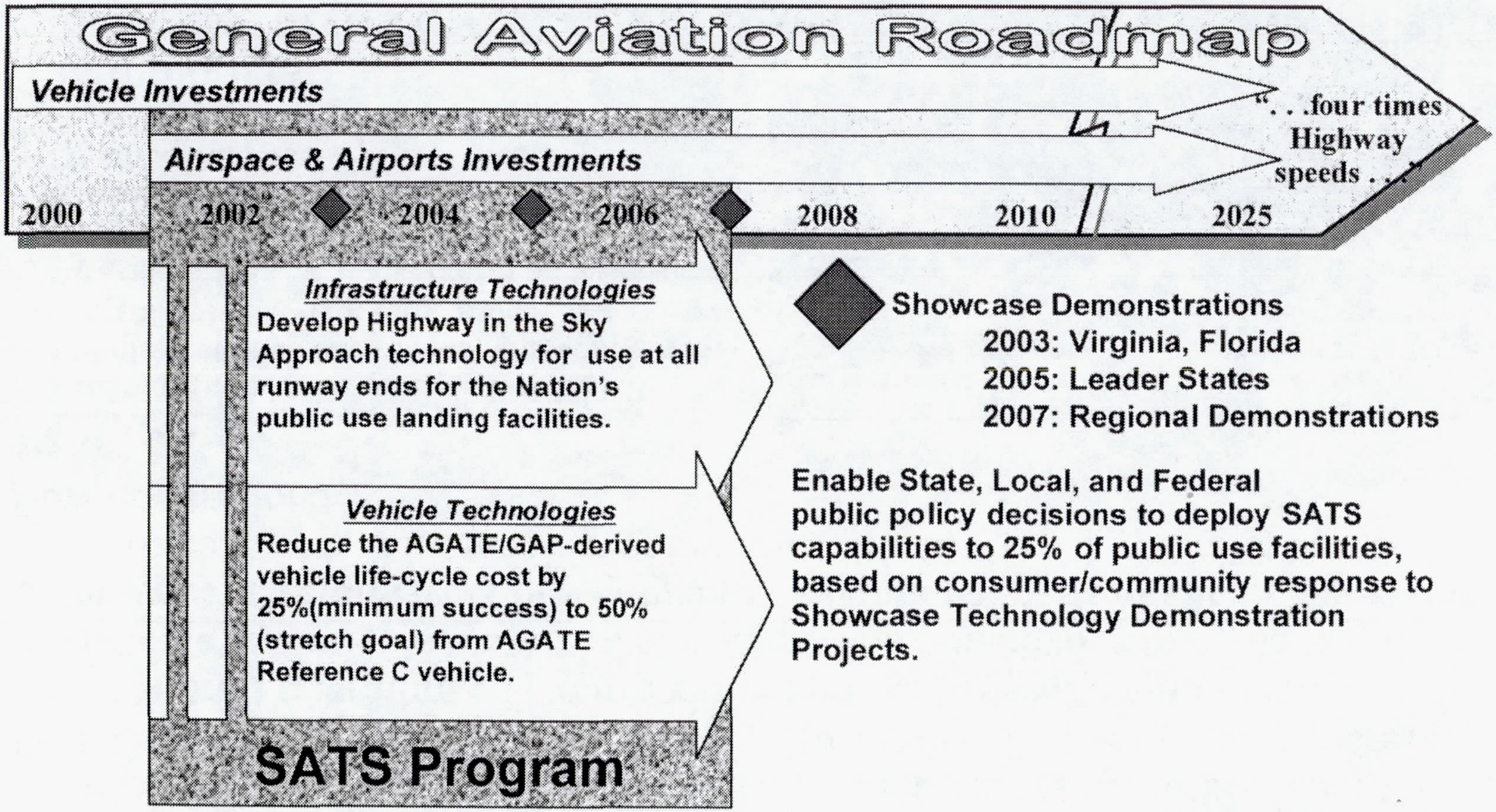
Technologies:

- **Operator interface design and human/automation task allocation**
- **Automatic intelligent controls, health monitoring & guidance**
- **Decoupled controls**
- **Envelope protection**
- **Voice command**

III A. SATS Program Description

NASA Office of Aero-Space Technology

Safe Air Accessibility for Information Age Communities



◆ Showcase Demonstrations

2003: Virginia, Florida

2005: Leader States

2007: Regional Demonstrations

Enable State, Local, and Federal public policy decisions to deploy SATS capabilities to 25% of public use facilities, based on consumer/community response to Showcase Technology Demonstration Projects.

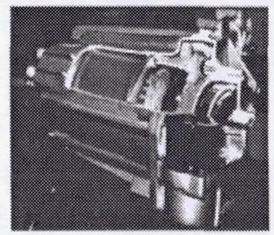
Ultra-Propulsion

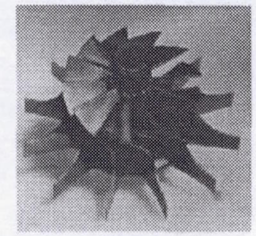
NASA Office of Aero-Space Technology | Safe Air Accessibility for Information Age Communities

Whisper-quiet, maintenance-free, clean small engines and non-hydrocarbon-based propulsion technologies will result in imperceptible emissions and noise assuring passenger comfort and community acceptance of aircraft operations

Features:

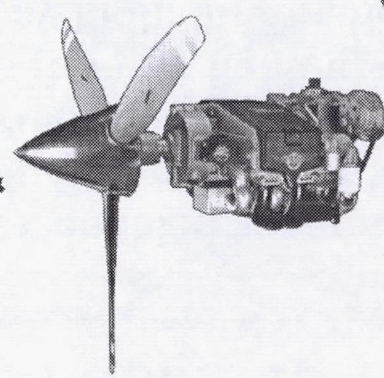
- **Ultra-Safe**
- **Ultra-Reliable**
- **Automobile like ultra-affordability**
- **Assured community/customer acceptance**

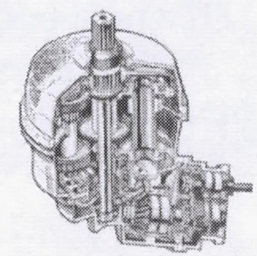




Technologies:

- **Electric propulsion & non-hydrocarbon fuels**
- **Whisper-quiet engines, transmissions & propulsors**
- **Low-cost ultra-low emissions combustion**
- **Automated, intelligent, fail-safe, controls & health monitoring**
- **Simple, intuitive operator interface**
- **Failsafe, low-cost composite structures**





"Smart" Landing Facilities

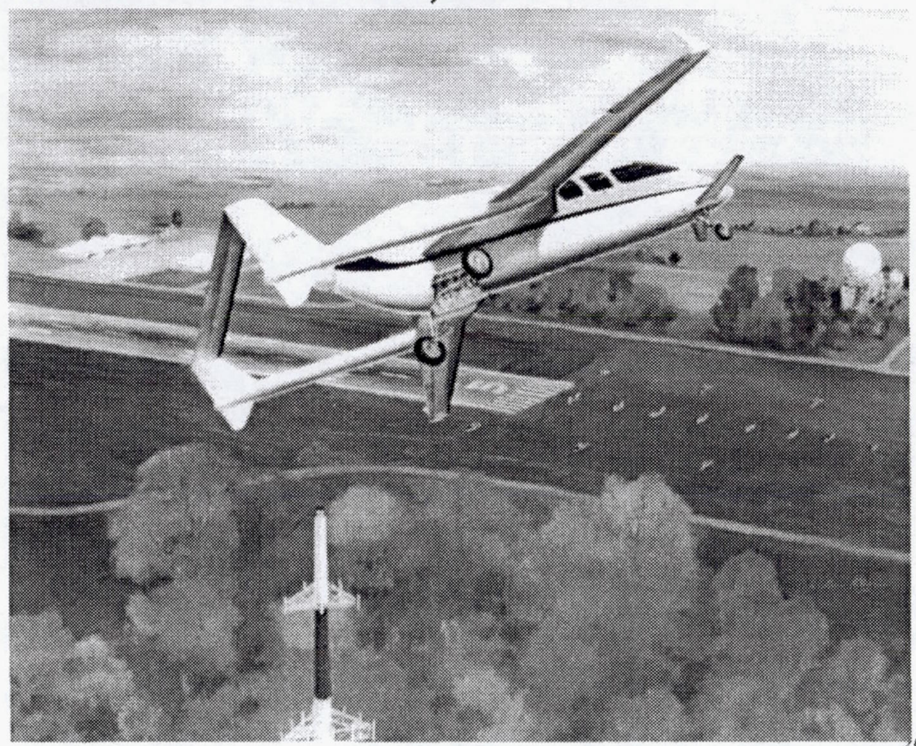
NASA Office of Aero-Space Technology

Safe Air Accessibility for Information Age Communities

"Smart Landing Facilities" provide automation-enabled separation and sequencing in non-towered, non-radar, non-hub terminal airspace and simultaneous non-interfering operations for runway-independent aircraft at hubs. Landing facility information and status (runway lighting and condition) will be provided to airborne nodes (vehicles) by flight information service (FIS) including weather, traffic, flight plans, etc. while the commercial service (CIS) will provide maintenance, fueling, intermodal connection, and other information.

Functions:

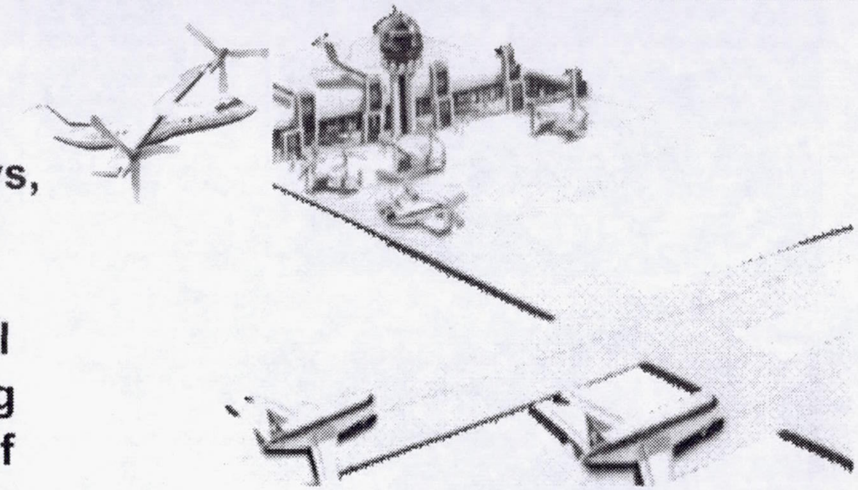
- Aircraft separation and sequencing
- Real-time weather
- DGPS Corrections
- Maintenance, Repairs & Services
- Personalized Dispatch Services
- Intermodal Connectivity (ground & air)
- Food & Lodging Info.
- Recreation Info.



Runway Independent Aircraft Operations

NASA Office of Aero-Space Technology | Safe Air Accessibility for Information Age Communities

The Runway Independent Aircraft operations will increase hub & spoke airport throughput by using stub runways, taxiways, & vertiports instead of conventional runway under adverse weather conditions. Differential GPS will enable Simultaneous and Non-Interfering (SNI) operations possible independent of fixed wing traffic within the ATM System.



Functions:

- Provide simultaneous and Non-Interfering hub airport operations including approach & departure paths independent of fixed wing traffic
- Seamless connectivity between hub and small landing facilities
- Low noise flight paths
- Stimulate development of future V/STOL & STOL aircraft

Affordable Manufacturing

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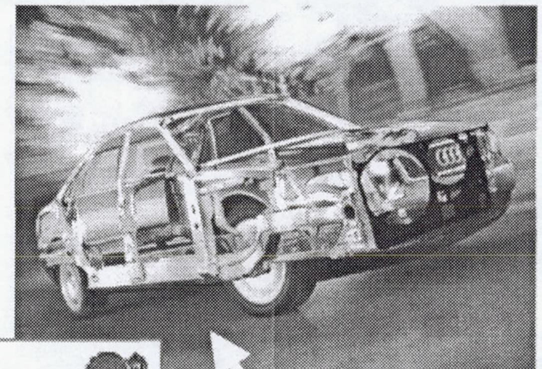
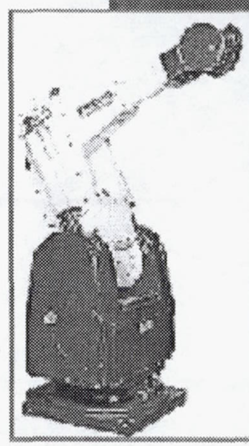
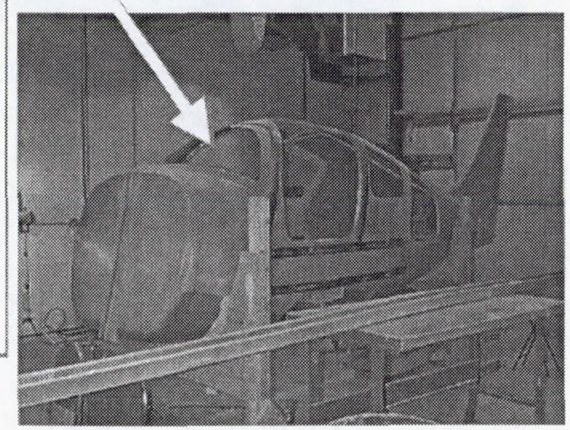
Low-cost manufacturing to integrate safety-enabling technologies at costs 25% (minimum success requirement) to 50% (goal success requirement) less than AGATE/GAP Reference C aircraft baseline

Features:

- **High-volume lean production**
- **Minimal hand labor (robotic labor)**
- **Certification integral to design & manufacturing processes**
- **Automotive safety technologies (air-bags, energy-absorbing structures, etc.)**







Technologies:

- **Robotic manufacturing**
- **Composite material systems**
- **Component-level certification reform**
- **Integrated ice & lightning protection**

Cyber-Tutor Training

NASA Office of Aero-Space Technology

Safe Air Accessibility for Information Age Communities

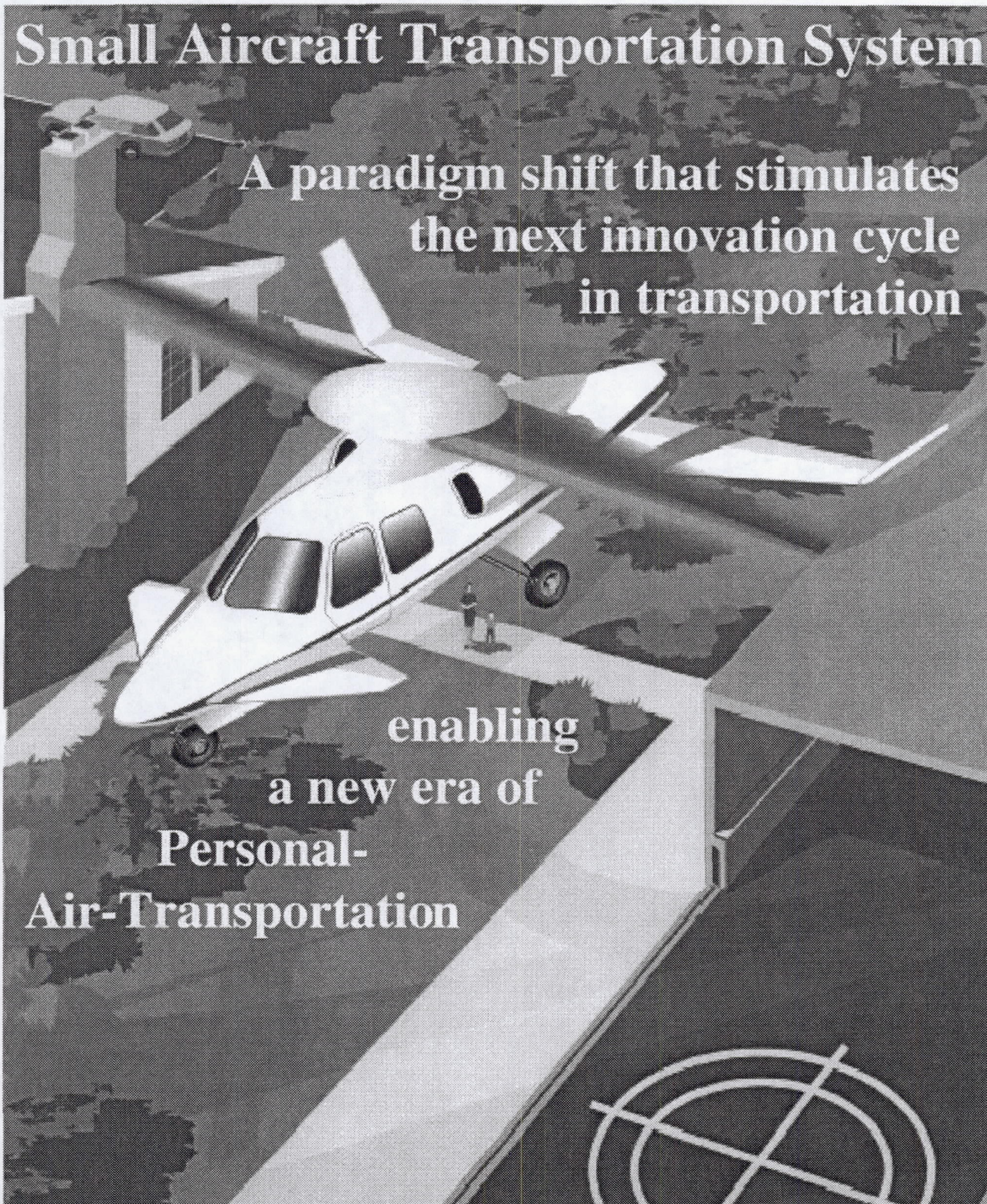
Integrate advanced training technologies to reduce training time & cost to obtain and maintain all-weather safe flying skills. Reduce training cost and calendar time by 50% from present standards

Features:

- **Unified Instrument-Private Curriculum for Highways in the Sky Systems**
- **Hazardous weather avoidance**
- **Emergency and abnormal operating procedures in AGATE-derived aircraft**
- **Turbojet pilot training for GAP-powered aircraft**

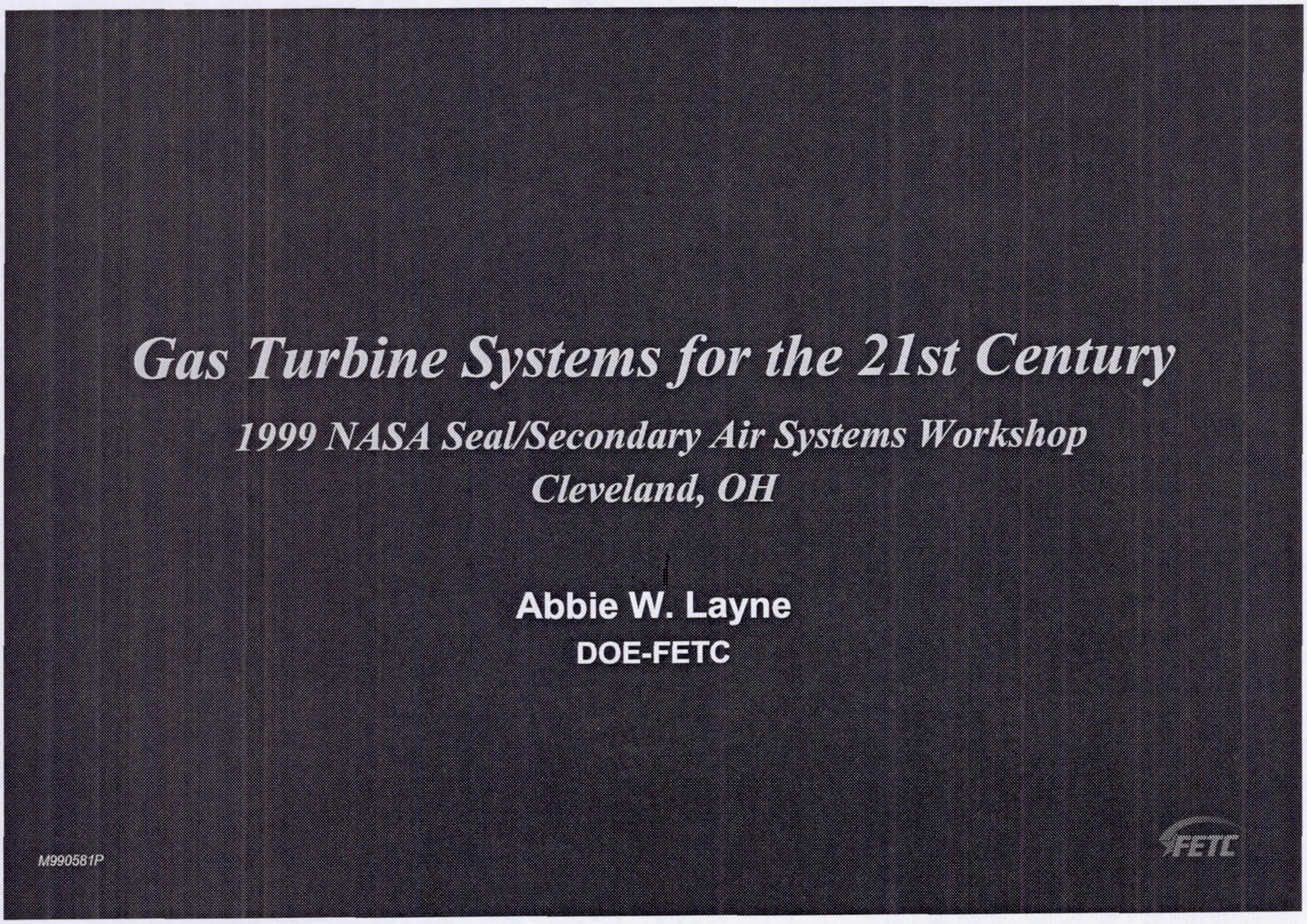
Technologies:

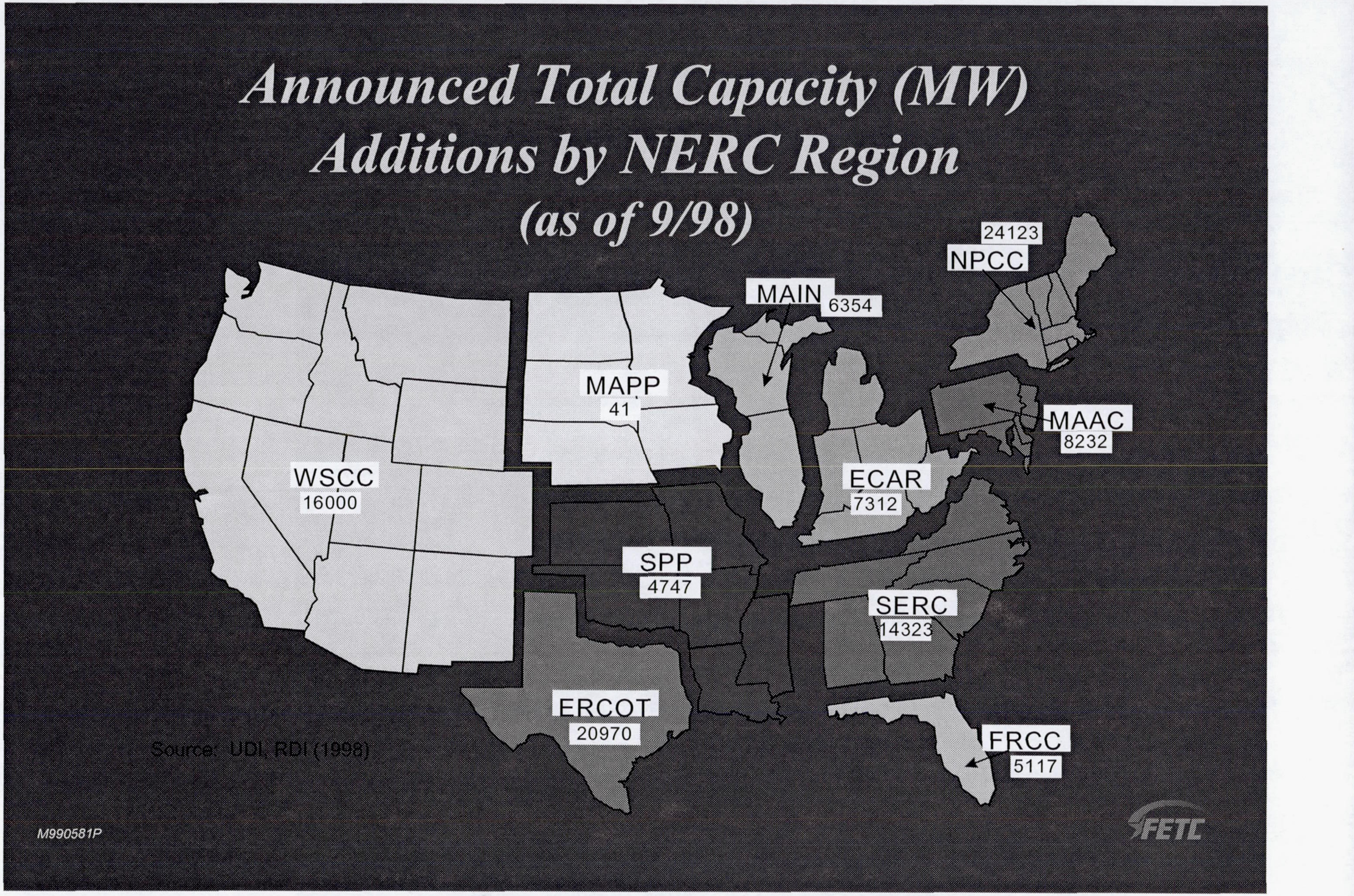
- **Lower-cost, higher-fidelity simulation**
- **Self-training capability**
- **Onboard, embedded training**
- **Web-based learning**
- **Computer-based training**


Small Aircraft Transportation System
A paradigm shift that stimulates
the next innovation cycle
in transportation
enabling
a new era of
Personal-
Air-Transportation
CD-98-77423

GAS TURBINE SYSTEMS FOR THE 21st CENTURY

Abbie W. Layne
Department of Energy FETC
Morgantown, West Virginia




Announced Total Capacity (MW)
Additions by NERC Region
(as of 9/98)
24123
NPCC
MAIN
6354
MAPP
41
MAAC
8232
WSCC
16000
ECAR
7312
SPP
4747
SERC
14323
ERCOT
20970
FRCC
5117
Source: UDI, RDI (1998)
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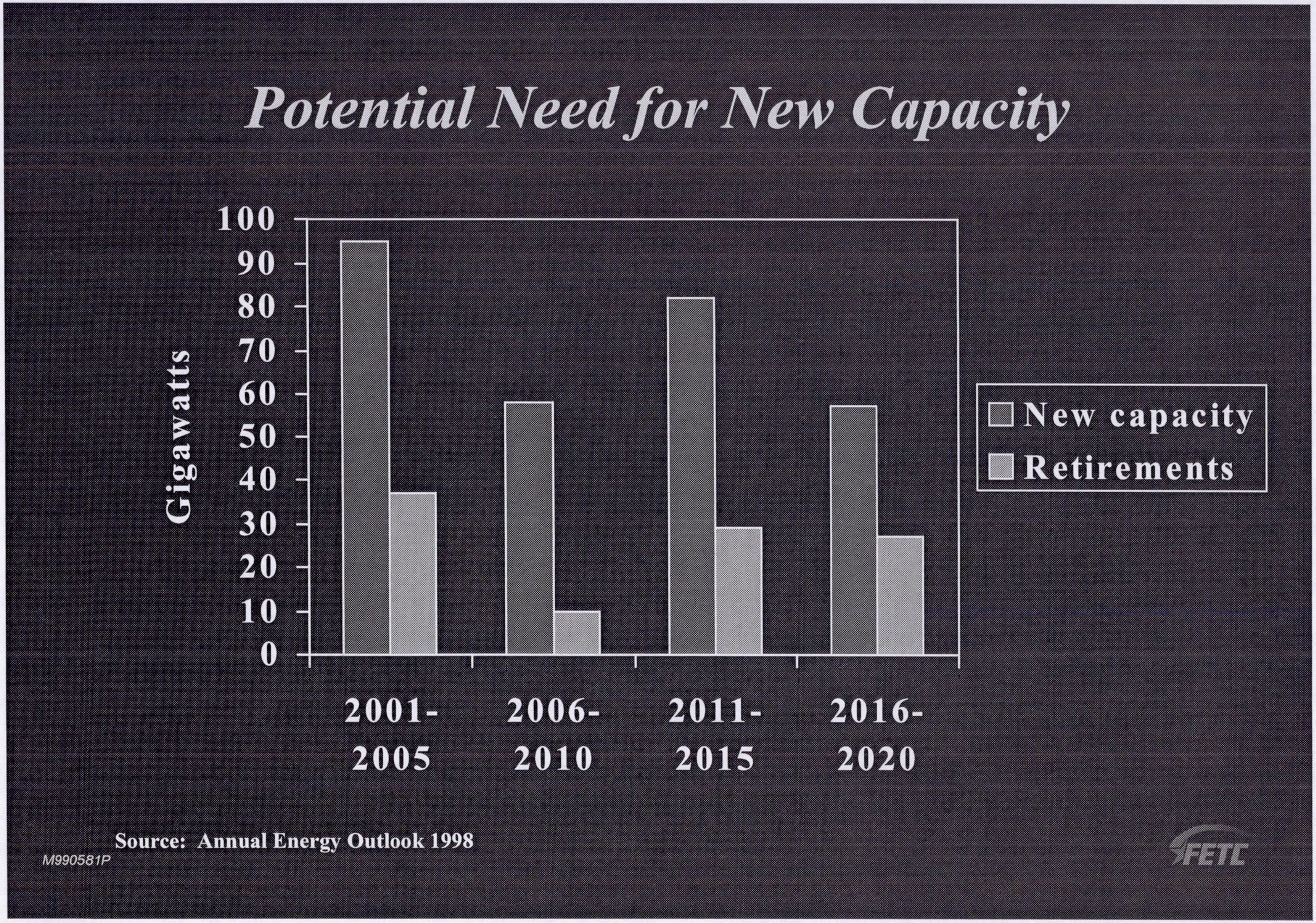
FETC


Potential Need for New Capacity
Gigawatts
100
90
80
70
60
50
40
30
20
10
0
2001-2005
2006-2010
2011-2015
2016-2020
New capacity
Retirements
Source: Annual Energy Outlook 1998
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Objective: ATS Program

- **By 2000 develop ATS for utility and industrial applications that are:**
  - Ultra-high efficiency: >60% for utility scale systems; 15% improvement for industrial system
  - Super-clean: NOx <10 ppm
  - Cost of electricity 10% lower
  - Fuel flexible: Gas primary focus

Leapfrog in Turbine Performance

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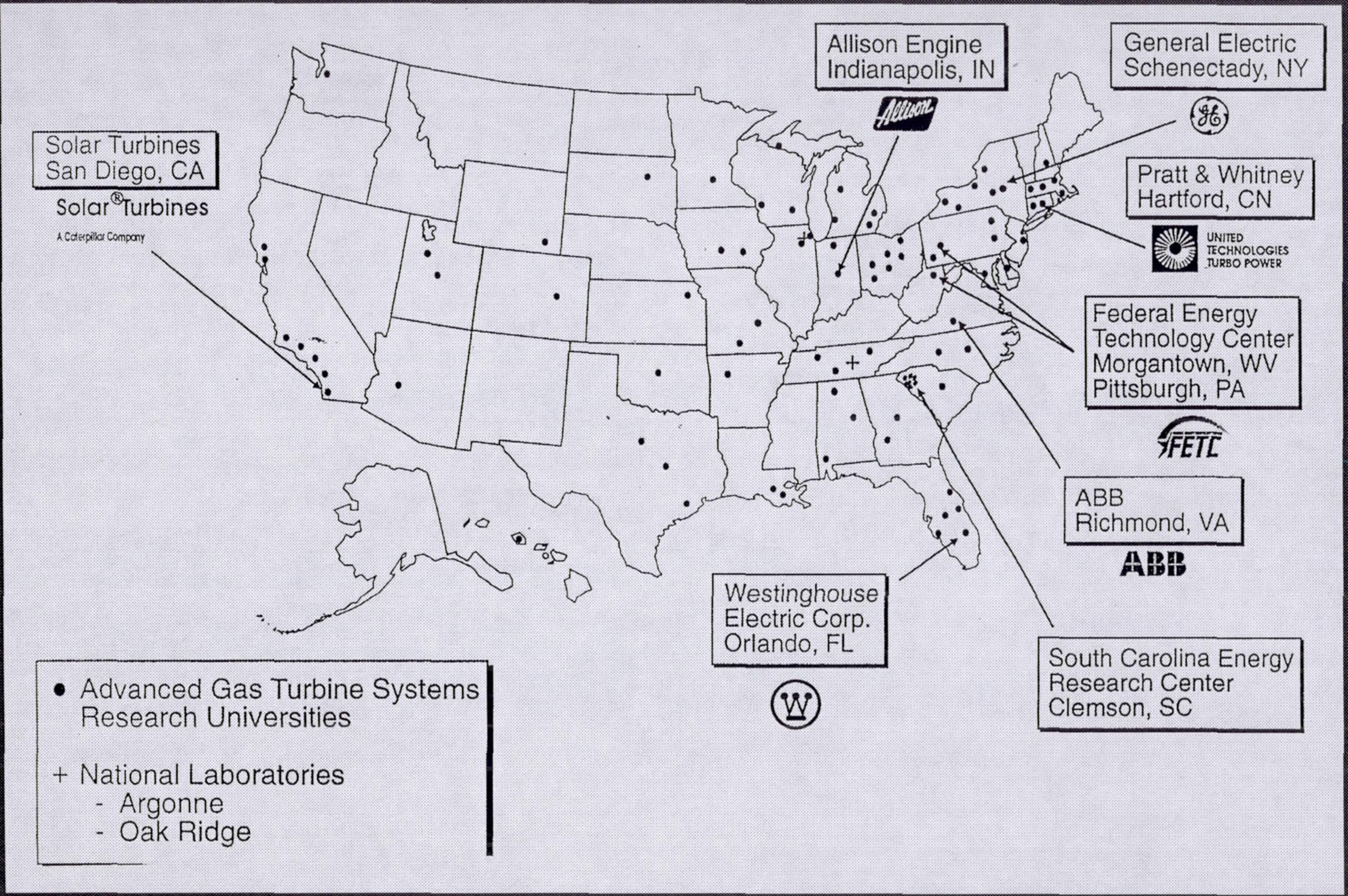
The Advanced Turbine System Program Participants

A Consortium of Universities, National Laboratories, U.S. Government, and Private Industry in 37 U.S. States



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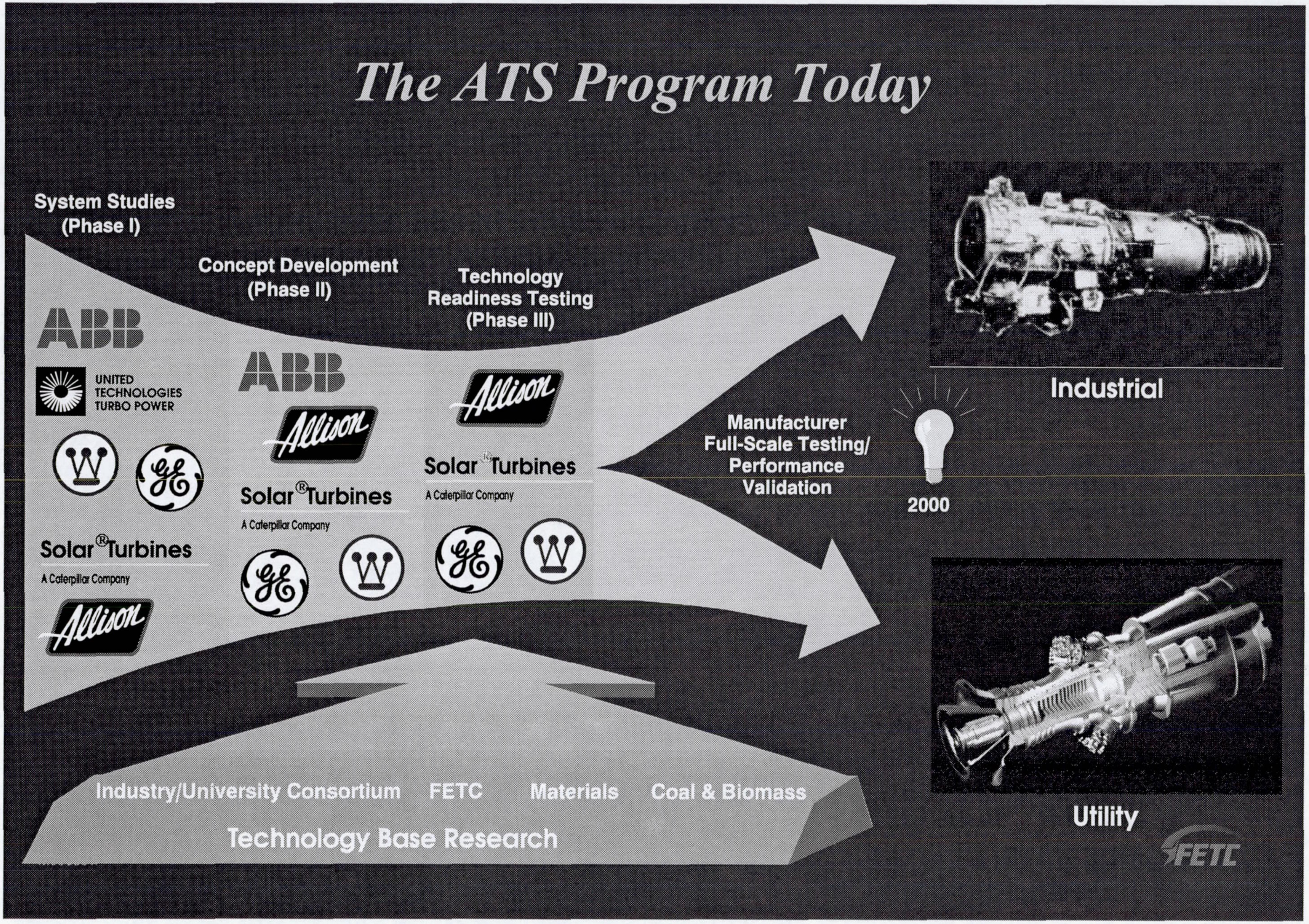
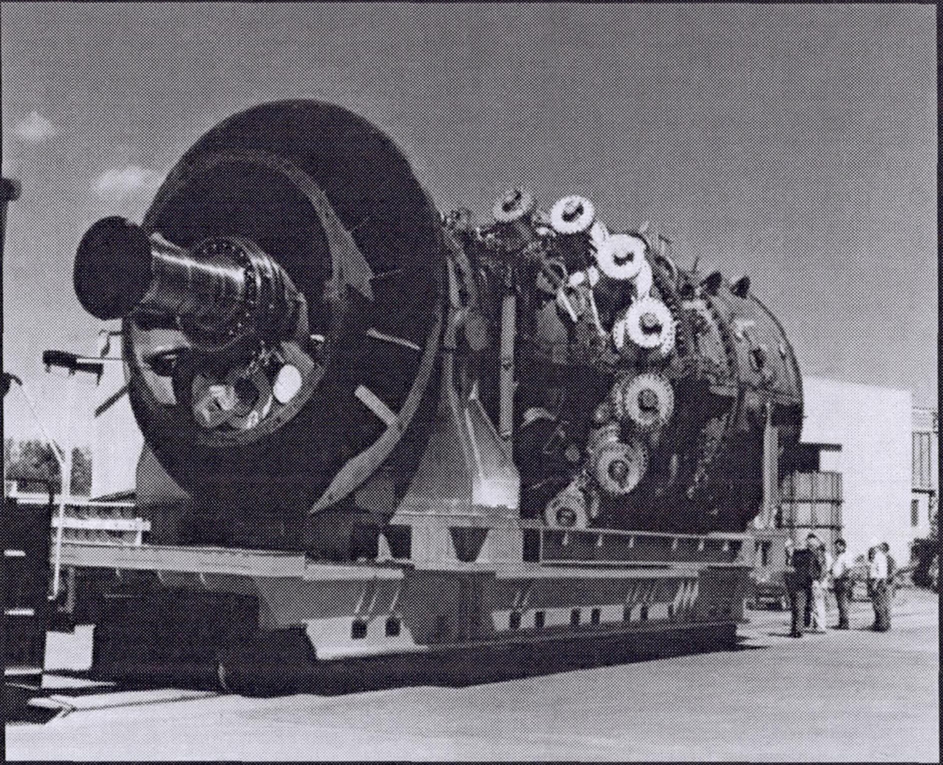


The ATS Program Today
System Studies
(Phase I)
Concept Development
(Phase II)
Technology
Readiness Testing
(Phase III)
ABB
UNITED
TECHNOLOGIES
TURBO POWER
Solar®Turbines
A Caterpillar Company
Allison
ABB
Allison
Solar®Turbines
A Caterpillar Company
Allison
Solar®Turbines
A Caterpillar Company
Manufacturer
Full-Scale Testing/
Performance
Validation
2000
Industrial
Utility
Industry/University Consortium FETC Materials Coal & Biomass
Technology Base Research
FETC

General Electric Company

Turbine System Development and Testing

- Completed full scale testing of 9H(50Hz)ATS, Greenville SC
- Complete 7H(60Hz) ATS testing in 2000, Greenville SC
- Conduct pre-commercial demonstration of 7H ATS in 2001



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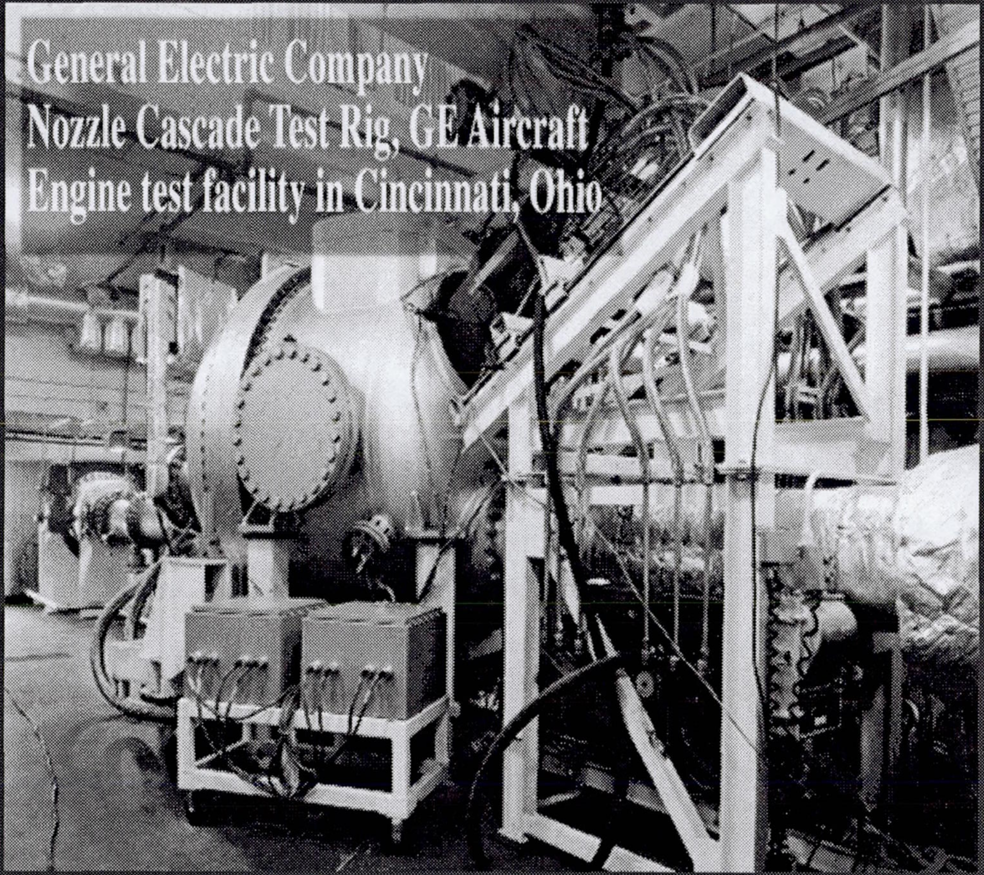
General Electric Company

Validation and Testing Program

- Full pressure combustion system at GE High Pressure Test Facility, Ohio
- Sub-scale compressor testing- GE Aircraft-, Lynn MA
- Steam cooled nozzle at GE High Pressure Test Facility, Ohio



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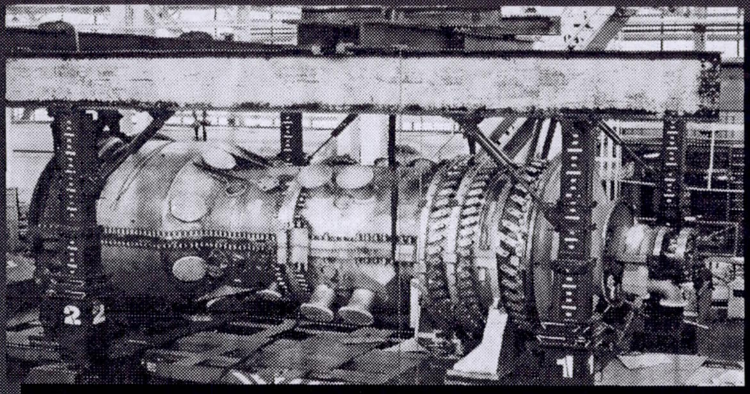
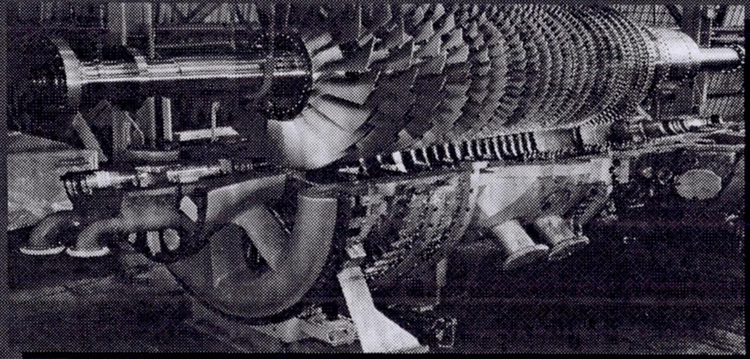
Siemens-Westinghouse Power Corporation

Turbine System Development and Testing

- Continue field testing of catalytic combustion and steam cooled systems on 501G
- Develop steam cooled vanes and test on 501GS power plant in 2001
- Manufacture 501 ATS and ship to customer site in 2002
- Conduct pre-commercial demonstration on 501ATS in 2002





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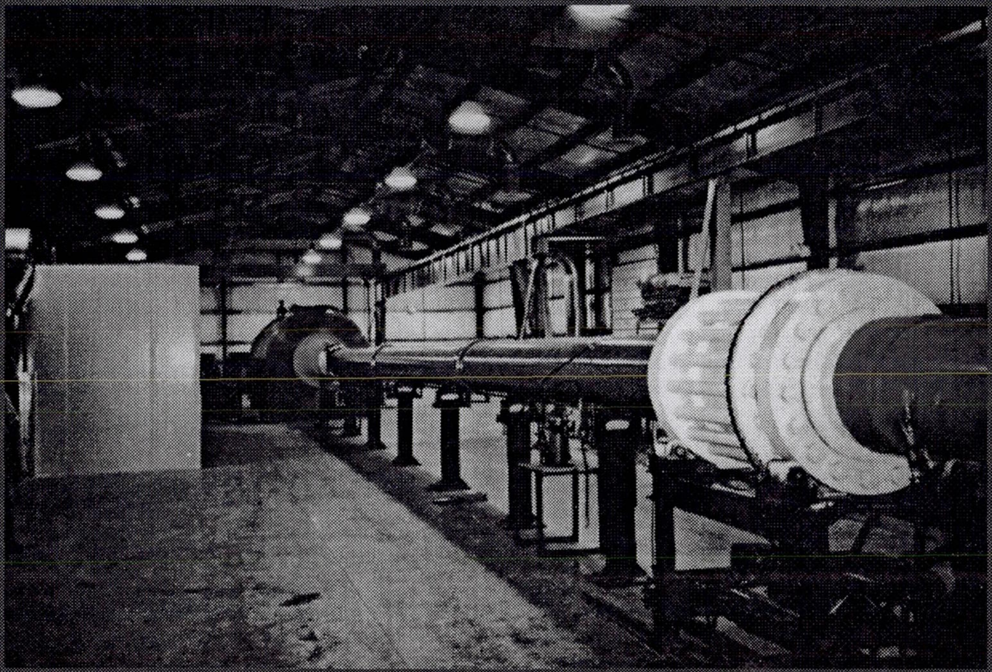
Siemens-Westinghouse Power Corporation

Validation and Testing Program



- Ohio State University Aerodynamic development testing on 1/3 scale model rig
- Catalytic combustion field testing on existing turbine
- Full scale steam cooled vane testing at Arnold Airforce Base

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FETC

Manufacturing Materials

Oak Ridge National Laboratory-FETC

Projects with: GE-PCC Airfoils, Siemens-Westinghouse, Howmet-GE-Solar

- Utility scale single crystal blades-reduced sulfur/no grain defects
- New core materials and processes, NDE
- Grain orientation control
- New projects - cost reduction; increased yield rates

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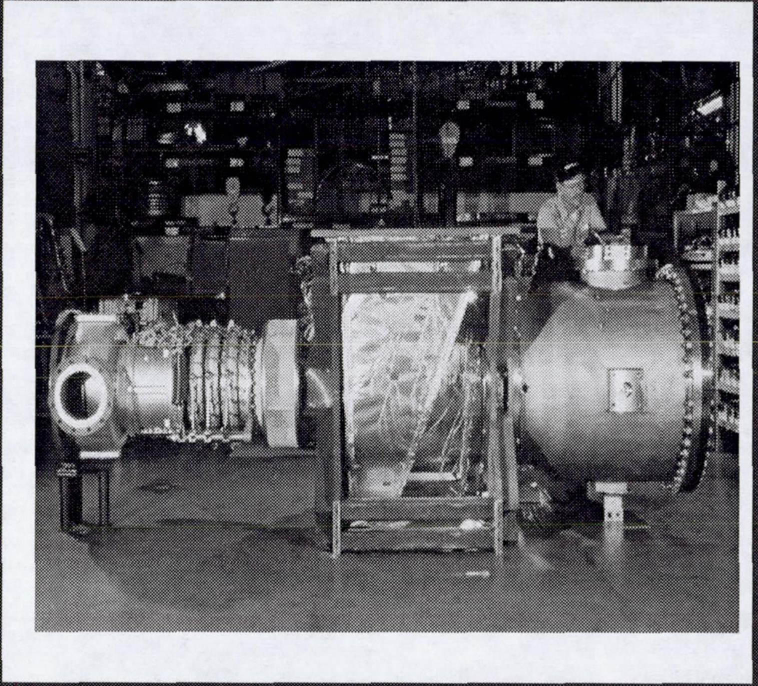
Solar Turbines

Technology R&D and Demonstration Program

- Mercury 50- 1st engine in production
- demonstration site is Rochelle Foods/Rochelle Municipal Utilities
- 40% + efficiency, single digit emissions
- 4.3 MW output



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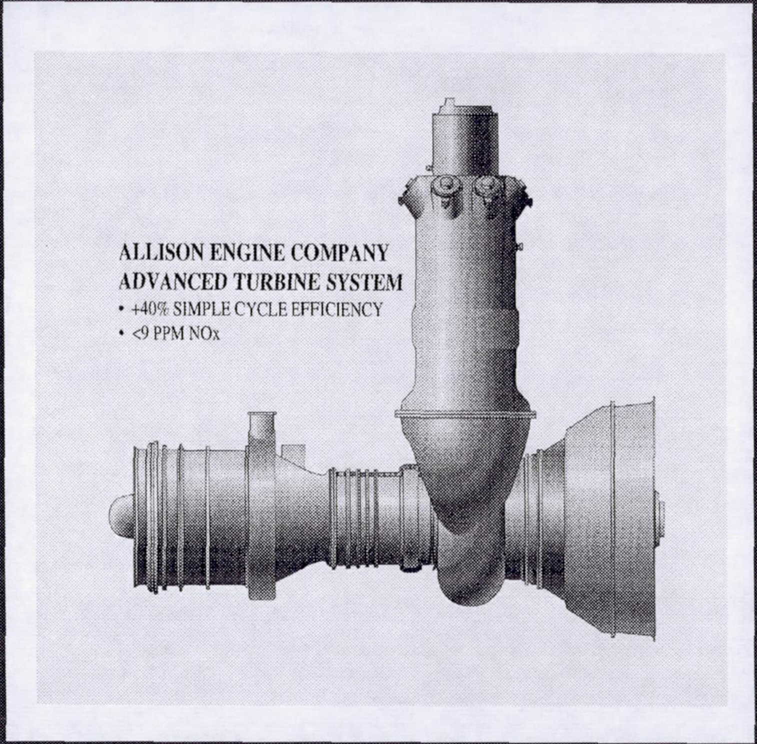
Allison Engine Company

Technology R&D Program

- **Focus on advanced technology to meet ATS development goals**
- **ceramic vanes**
- **low emissions combustion**
- **technology to advance current engines to ATS goal vs. new engine development**



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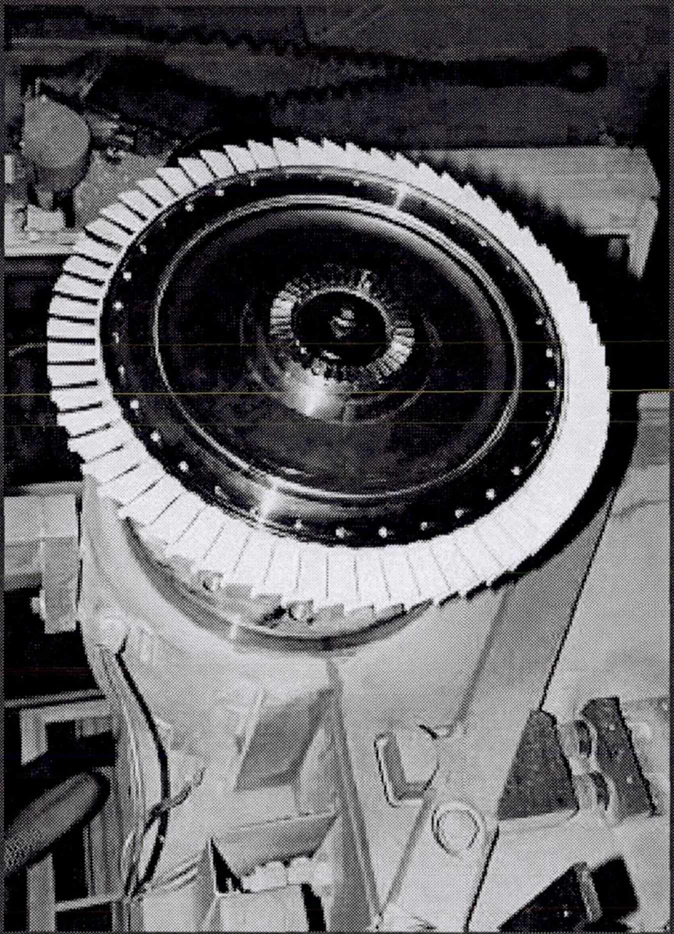
Ceramic Stationary Gas Turbine Developments-ARCO Western Energy

- 4000 hours of ceramic blades
- CFCC combustion liner testing for >5000 hours
- First stage nozzle SN88 installed
- total testing time accumulated 4000 hours



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Industry/University Consortium

SCIES

Industry/Research Consortium

- 95 Performing Member Institutions
- 37 States Represented
- 6 RFP's Announce
- 8 Industrial Manufactures

Education Program

- Undergraduate Research Fellowships
- Industrial Internships
- Faculty Internships
- Short Courses

Workshops & Seminars

- Heat Transfer
- Materials
- Combustion

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Industry/ University Consortium- South Carolina Institute for Energy Studies

- A consortium of 95 U.S. universities in 37 states
- 51 ongoing projects with universities
- Topical Areas - Heat Transfer, Aerodynamics, Combustion, Materials
- Workshops, Internships, Sabaticals

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Next Generation Turbine and Engine Systems

- ***Fuel Cell Hybrid Systems(engines and turbines)***
  - High efficiency, low emissions
  - Distributed generation
  - Long Term Vision 21 systems
- ***Flexible Gas Turbine Systems***
  - Flexibility - operation, fuel, modularity
  - Efficiency improvements for existing fleet of power plants(coal, gas, oil)

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Next Generation Turbine and Engine Systems

- ***Vision 21-High Efficiency Engines and Turbines***
  - Advanced turbine cycles
  - Ultra high temperature, pressure
  - Reheat and/or inter-cooling
    Hydrogen/CO_2 turbines
- ***Advanced Reciprocating Engine Systems***
  - Distributed Power
  - Ultra high efficiency
  - Lowest emissions technology
  - Natural Gas fueled

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Rationale for Vision 21

- Removes environmental barriers to fossil fuel use
- Keeps electricity costs affordable
- Produces useful coproducts, e.g. liquid transportation fuels, at competitive prices
- Continues U.S. leadership role in clean energy technology
- Provides the most certain route to achieving our energy, environmental, and economic objectives

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Vision 21 Goals

- **Develop advanced technology modules for a new fleet of 21st century energy plants tailored to market demand:**
  - efficiency (to electricity) > 60 % on coal; > 75% on gas
  - overall thermal efficiency of 85 - 90%
  - near zero pollutant emissions
  - lower cost of electricity and fuels than today
  - cost effective management of carbon emissions
- **Establish mechanisms for deploying these advanced technologies, including industry and government partnerships**

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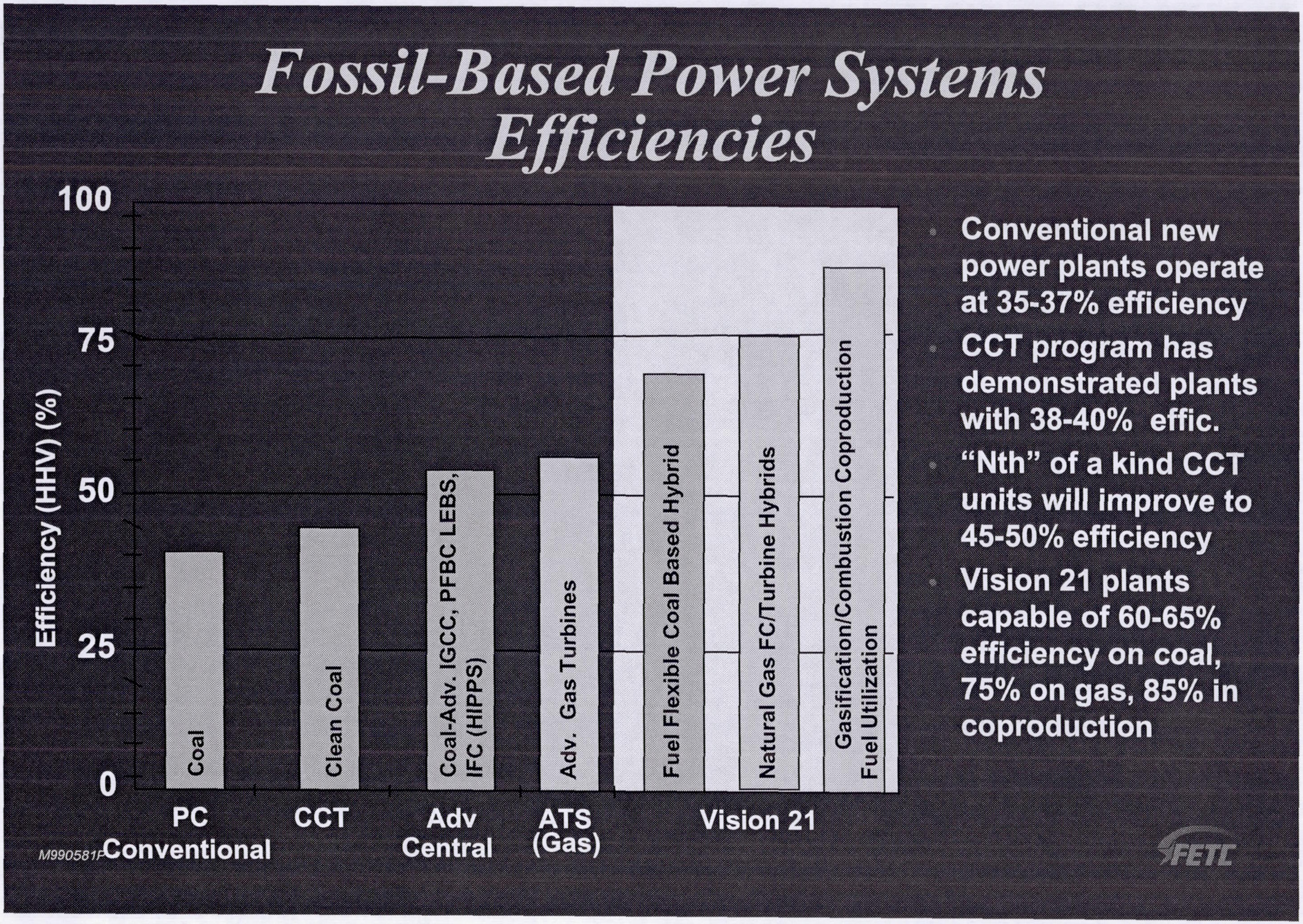
Fossil-Based Power Systems Efficiencies
Efficiency (HHV) (%)
100
75
50
25
0
Coal
Clean Coal
Coal-Adv. IGCC, PFBC LEBS, IFC (HIPPS)
Adv. Gas Turbines
Fuel Flexible Coal Based Hybrid
Natural Gas FC/Turbine Hybrids
Gasification/Combustion Coproduction Fuel Utilization
PC Conventional
CCT
Adv Central
ATS (Gas)
Vision 21
M990581P
Conventional new power plants operate at 35-37% efficiency
CCT program has demonstrated plants with 38-40% effic.
"Nth" of a kind CCT units will improve to 45-50% efficiency
Vision 21 plants capable of 60-65% efficiency on coal, 75% on gas, 85% in coproduction
FETC

Next Generation System Goals by year 2010

System Size- 30-150MW

Improved Design Efficiency	45-50%
Cost of Electricity	15-20% below market
Service life	No greater than ATS
Reduced carbon emissions	Retrofitable
Market Penetration	25% of 2010 market
Dispatch flexibility	400 starts per year
Nox emissions	Meet any 2010 requirement
Reduce O&M costs	15% reduction from comparable product
Reduce capital costs	15% reduction from comparable product

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Vision 21 Fuel Cell/GT Cycle

Plant Performance Summary

Gasifier	Destec
Coal Input to Gasifier, lb/hr	256,142
Thermal Input, MW_t	875.8
HP SOFC Module, MW, dc/ac	189.4/182.8
LP SOFC Module, MW, dc/ac	121.4/117.2
Gas Turbine, MW	133.7
Steam Turbine, MW	118.0
Fuel Expander, MW	9.6
Gross Power, MW	561.3
Auxiliary Power MW	40.4
Net Power, MW	520.9
Efficiency, % HHV	59.5

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NASA/CP—2000-210472/VOL1

Next Generation Systems Will...

- Build on success of ATS program
- Result in significant air emissions reductions
- Accelerate the overall efficiency increase of the existing and new power generation fleets in the U.S.(coal,oil,gas)
- Develop an effective pathway to Vision 21 systems

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FULL SCALE TESTING OF AN ASPIRATING FACE SEAL WITH ANGULAR MISALIGNMENT

Norm Turnquist
General Electric Corporate Research and Development
Niskayuna, New York

Alan D. McNickle
Stein Seal, Co.
Kulpsville, Pennsylvania

Thomas W. Tseng
General Electric Aircraft Engines
Cincinnati, Ohio

Bruce M. Steinetz
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio

Full Scale Testing of an Aspirating Face Seal with Angular Misalignment

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Cincinnati, OH

B.M. Steinetz
NASA John H. Glenn Research Center
at Lewis Field
Cleveland, OH

1999 NASA Seal/Secondary Air System Workshop
October 28-29, 1999
NASA John H. Glenn Research Center at Lewis Field

Full Scale Testing of an Aspirating Face Seal with Angular Misalignment

Objectives

Develop an Aspirating Face Seal design for use in the GE90 aft outer LPT seal location, and other new and existing engines.

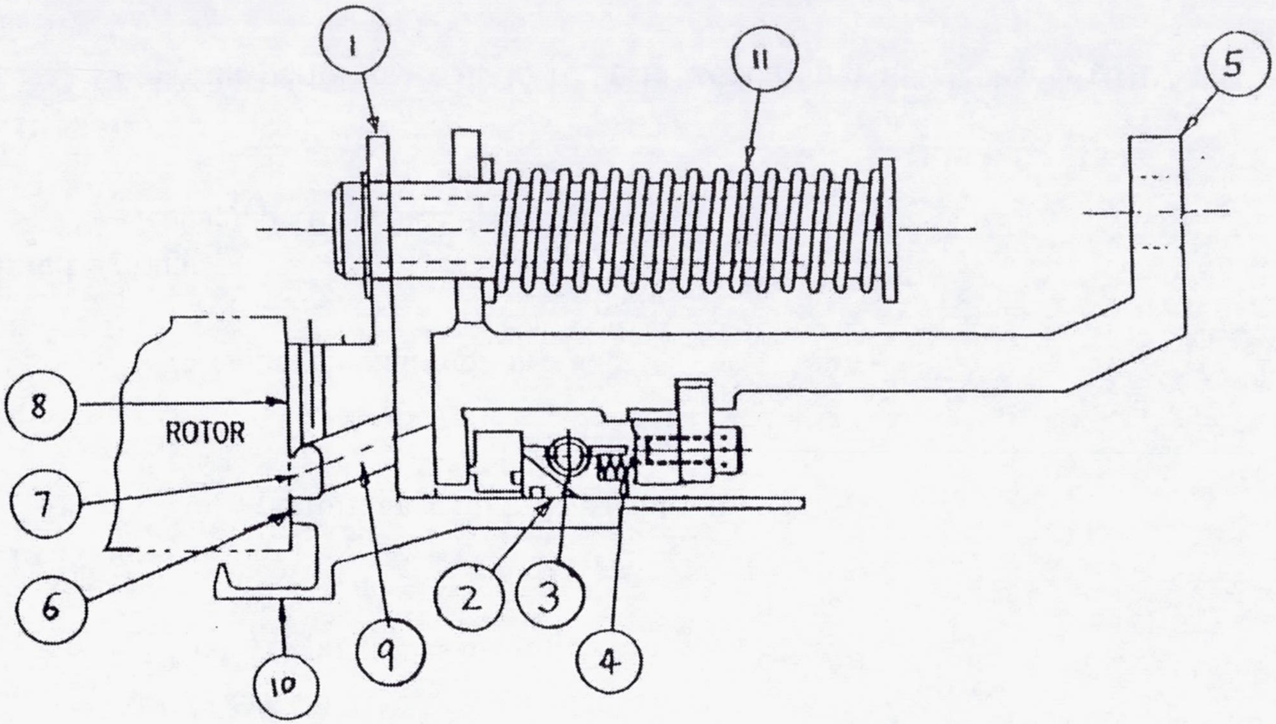
Motivation

Reduced secondary flow leakages result in SFC improvements.
Non-contact seal results in longer seal life, no performance degradation.

Outline

Enhanced Aspirating Seal Design
Test Plan & Facilities
Analytical Verification of Seal Design
Rig Modifications for Seal Tilt
Test Results
Conclusions

The 36" Diameter Aspirating Face Seal



- Hydrostatic gas bearing while closed
- Single tooth labyrinth while retracted
- Seal is normally retracted
- Non-contact
- All metal design
- Designed for 0.002" film thickness at operating pressure

The Test Plan

Plan must address all conditions seal is likely to encounter

1. Dust Ingestion
- 14.7” seal
- 0-10 micron particles at 1/3000 lb/sec

2. Static Leakage
- leakage performance up to 100 psid

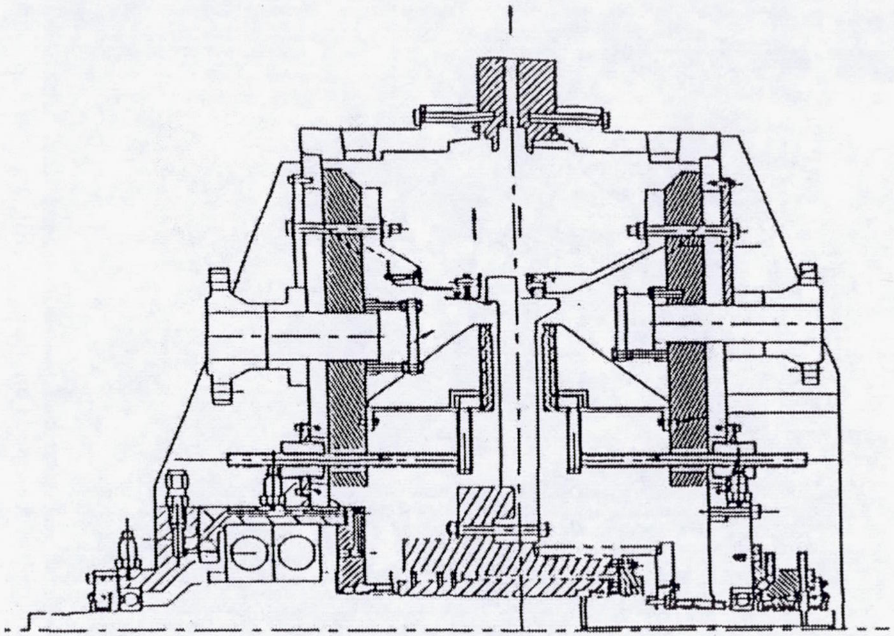
3. Tracking
- 0.75” relative axial motion

4. Dynamic Leakage
- leakage performance up to 100 psid, 2400 rpm, 750° F

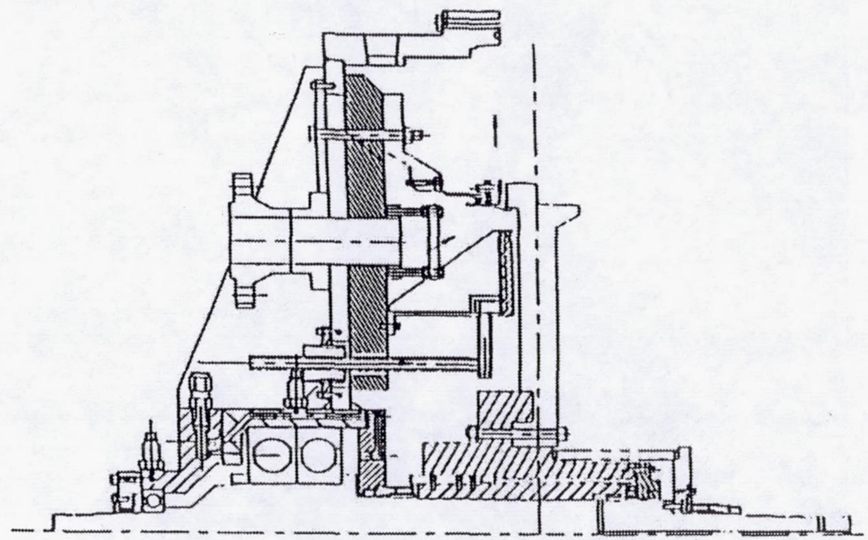
5. Rotor Runout
- leakage performance up to 100 psid, 2400 rpm with 0.005 and 0.010” TIR

6. Seal Tilt
- leakage performance up to 100 psid, 2400 rpm with 0.27° tilt

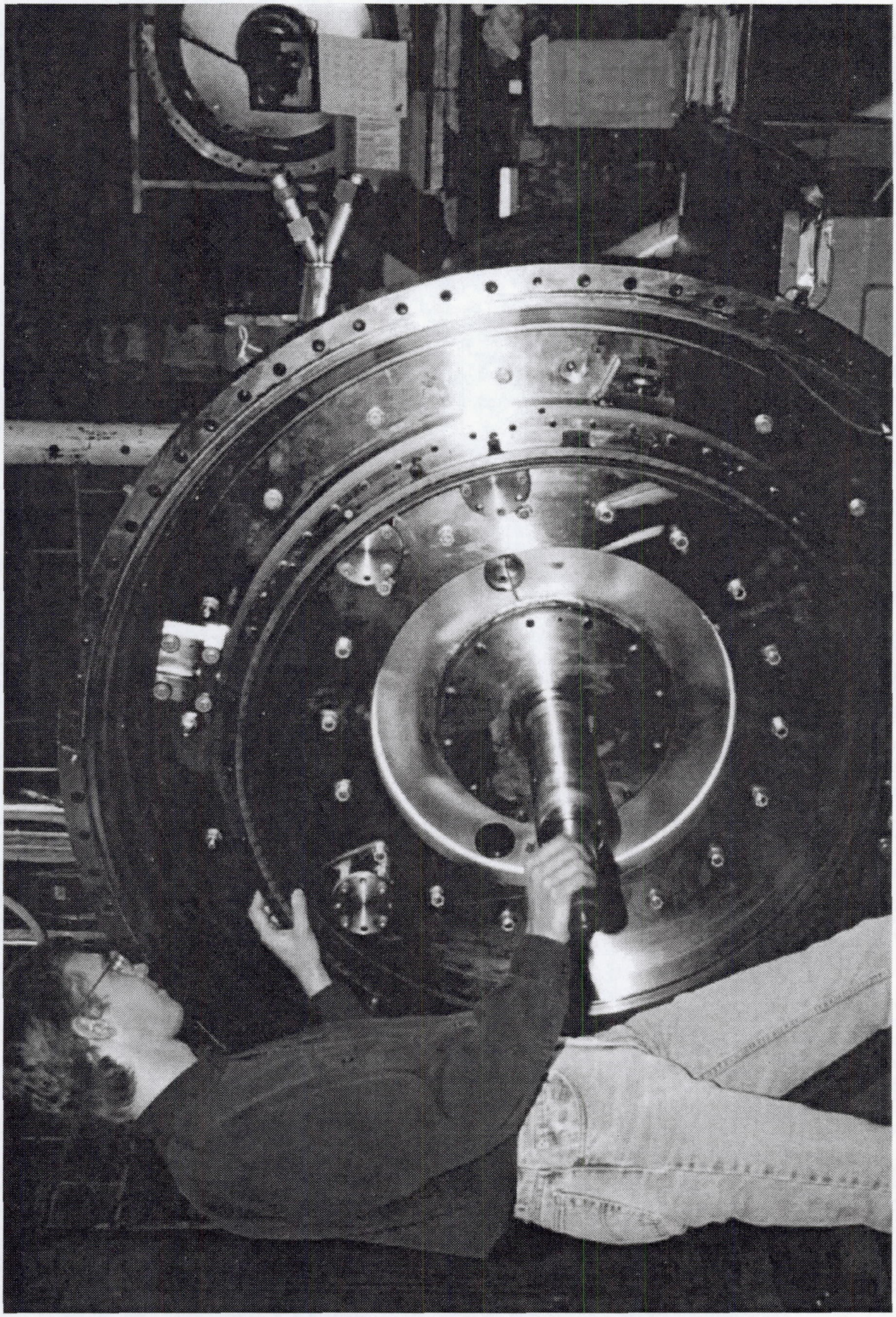
The Full Scale Test Rig



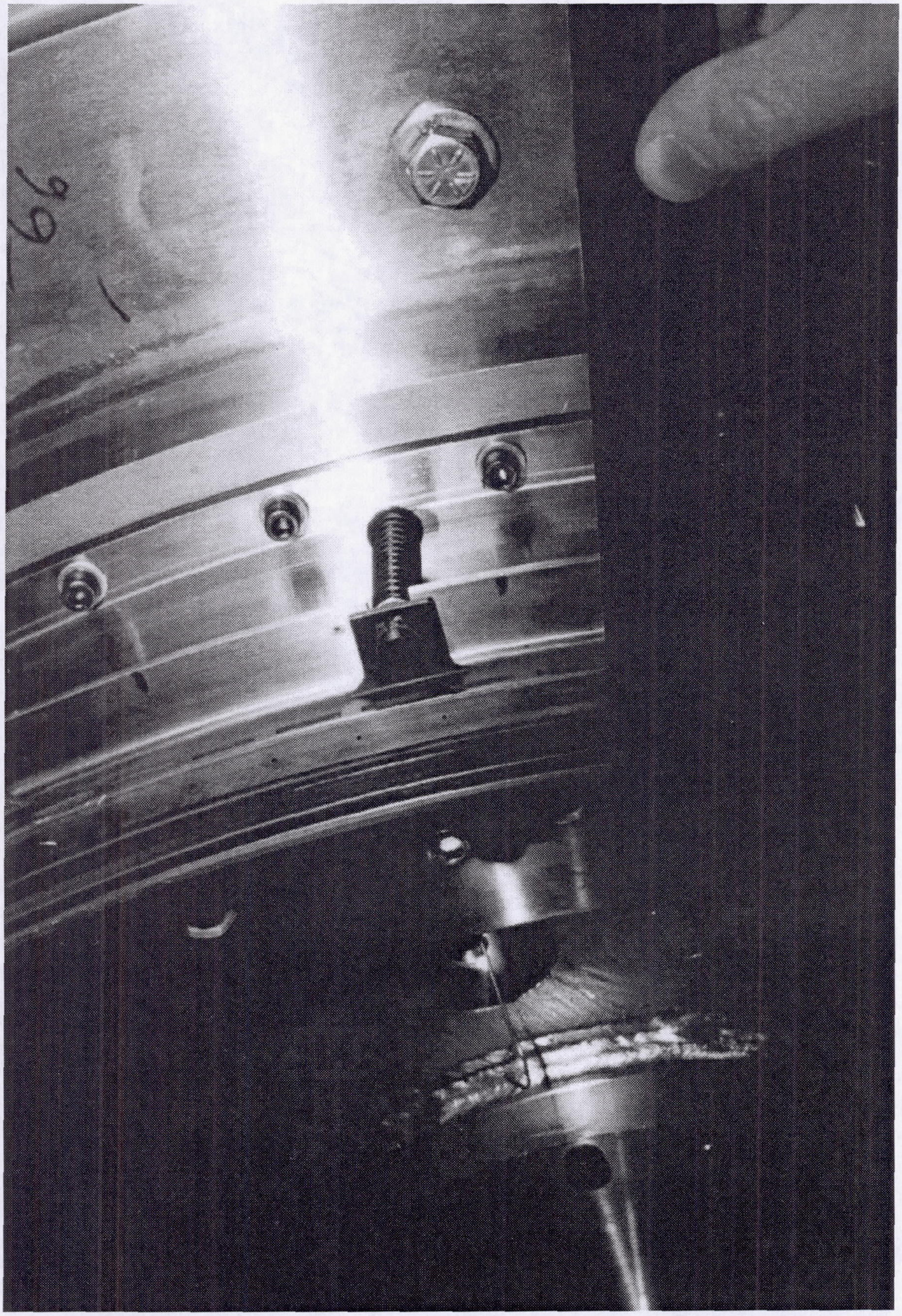
Fully Assembled
Rig Configuration



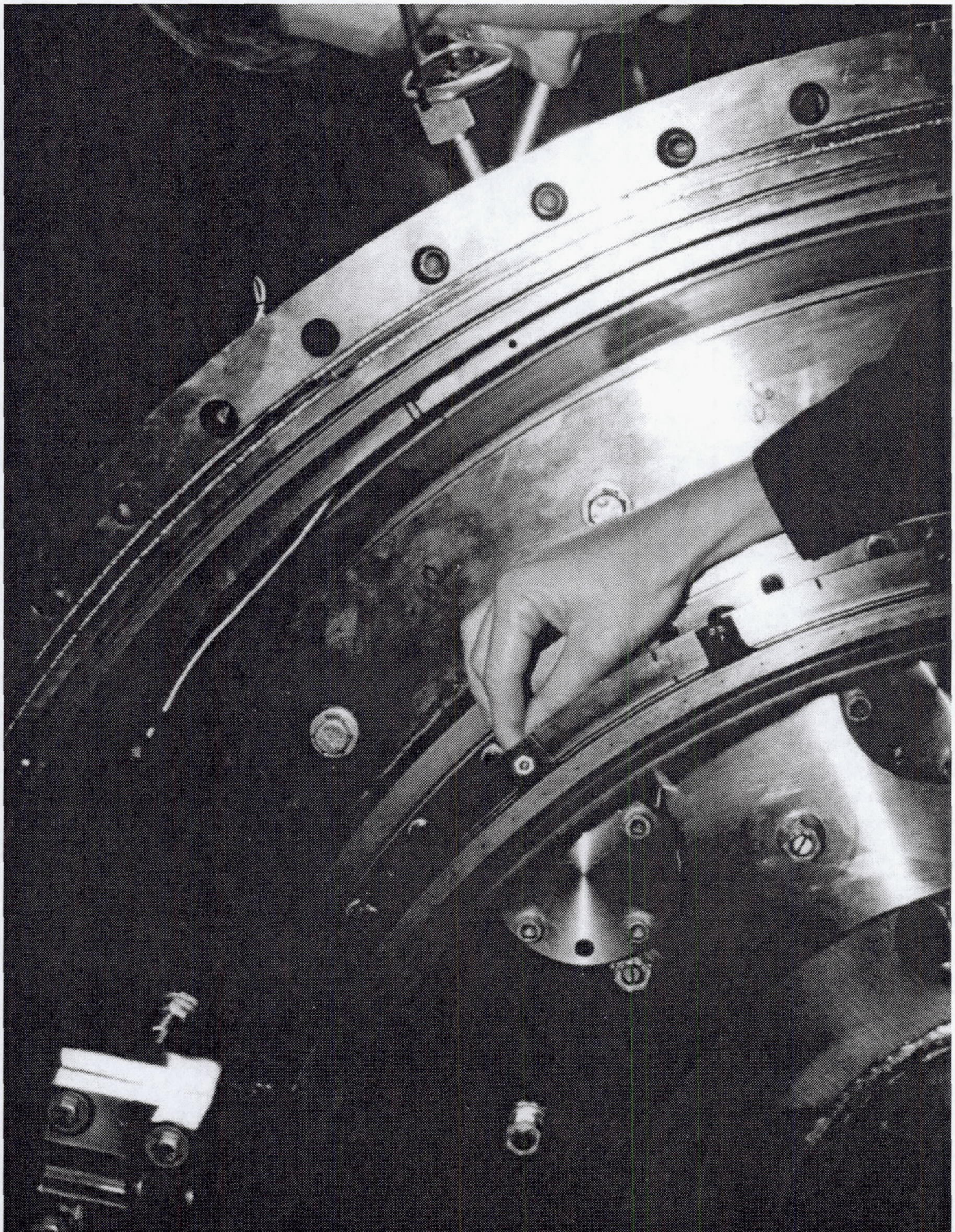
Open Vessel Test
Configuration



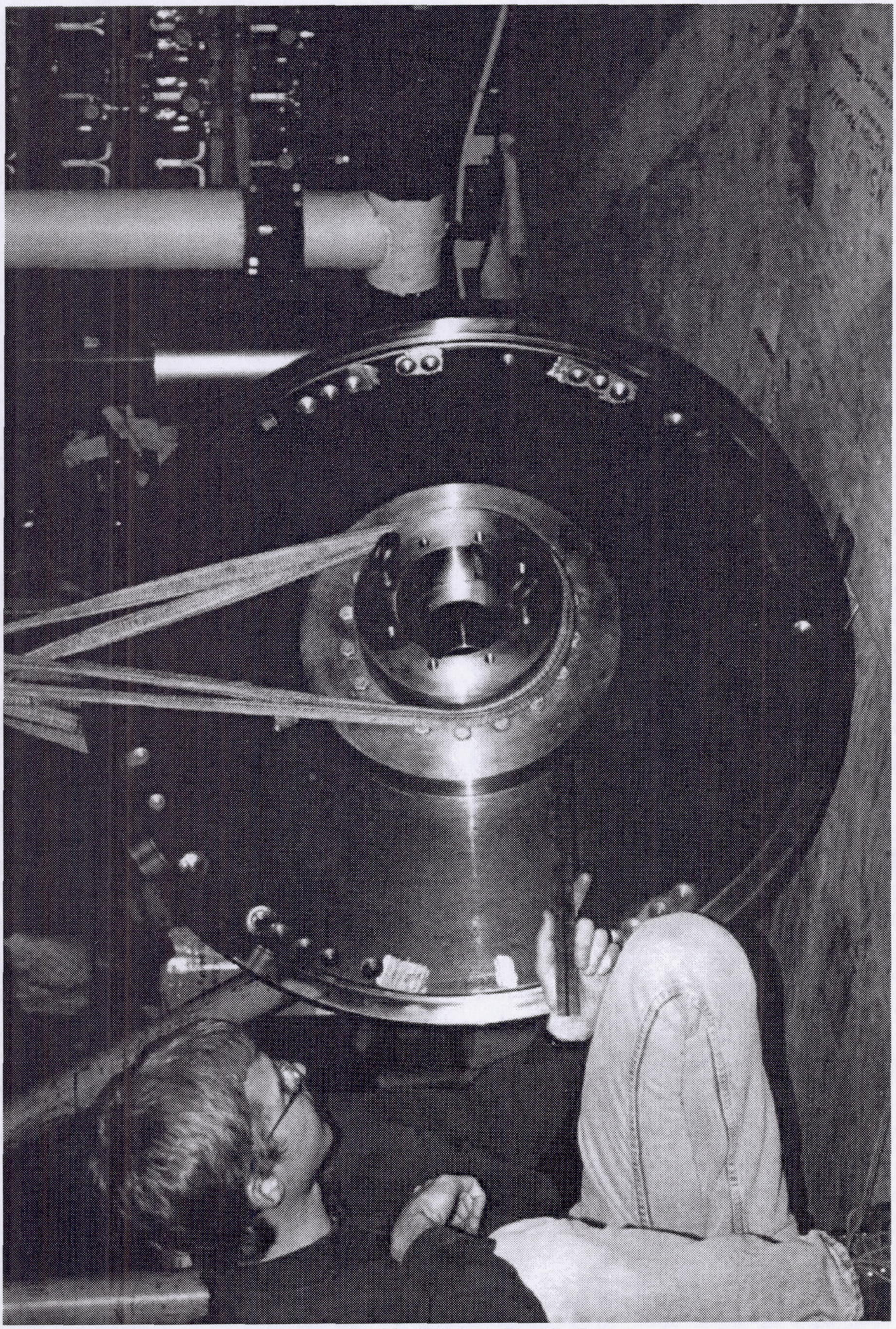
Photograph of the Open Full Scale Test Rig with the Aspirating Seal Installed



Detailed Photograph of the Aspirating Seal showing the Air Bearing Face and Orifice Holes

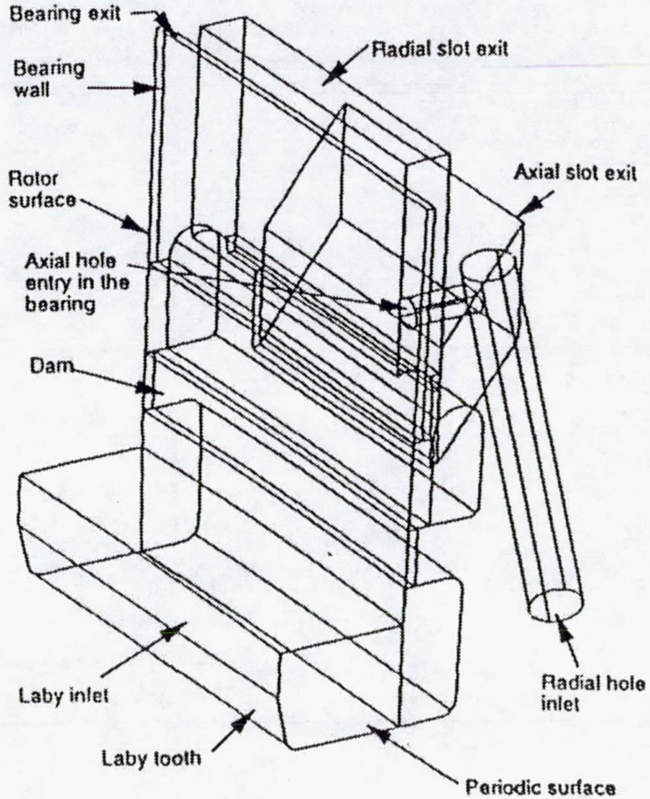


Photograph of the Aspirating Seal Installed in the Full Scale Test Rig showing Axial Contact Probe



Photograph of the Full Scale Test Rig Rotor

The CFD Model

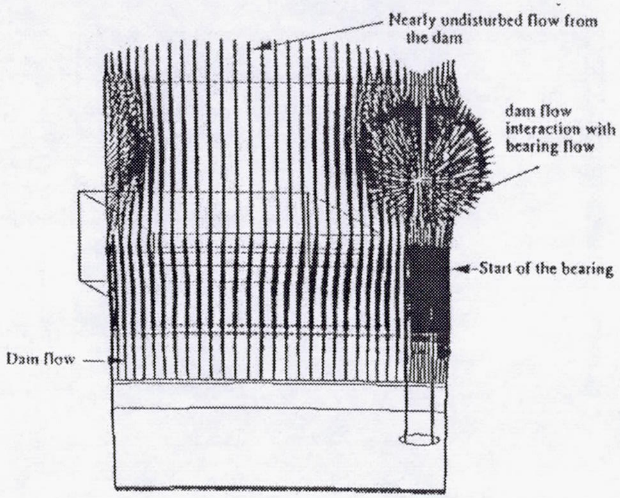


- 3-D Pie Sector of seal
- Includes labyrinth tooth, air dam, and hydrostatic air bearing
- Captures effect of discrete orifice holes in air bearing face

CFD Results - Flow Fields

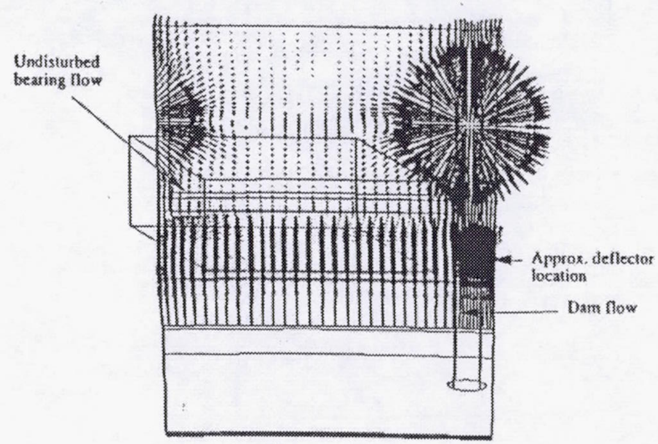
Original Configuration

Velocity field near rotor surface, baseline seal, 16 mils



With Flow Deflector

Velocity field near rotor surface, Seal with deflector, 16 mils

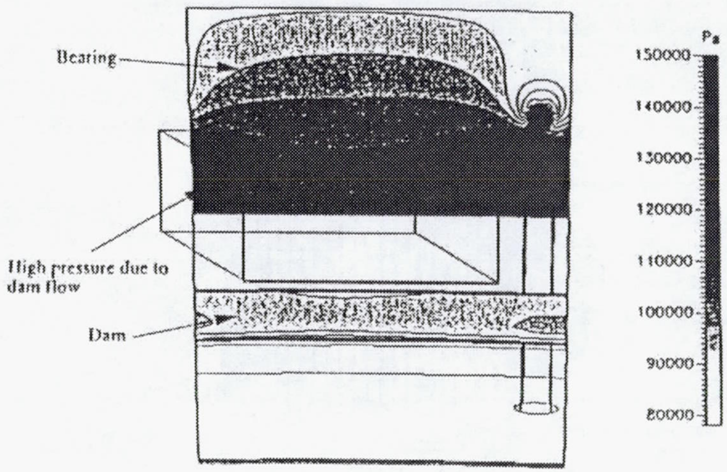


- Without deflector, air dam/air bearing flow mixing occurs.
- Deflector effectively isolates air dam/air bearing flows.

CFD Results - Pressure Distributions

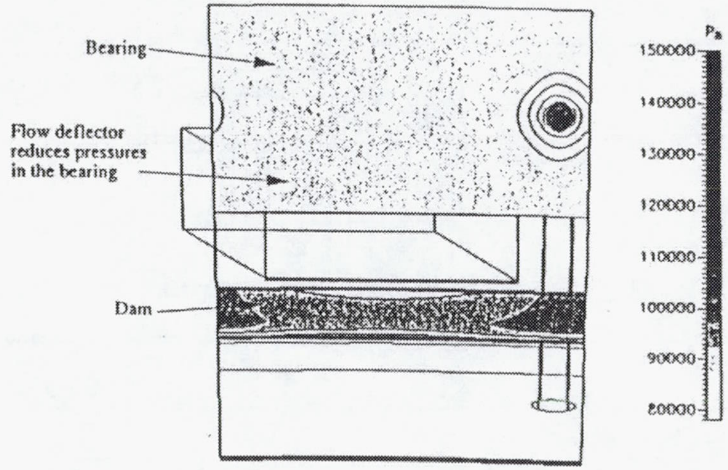
Original Configuration

Bearing and dam surface pressure, baseline seal, 16 mils



With Flow Deflector

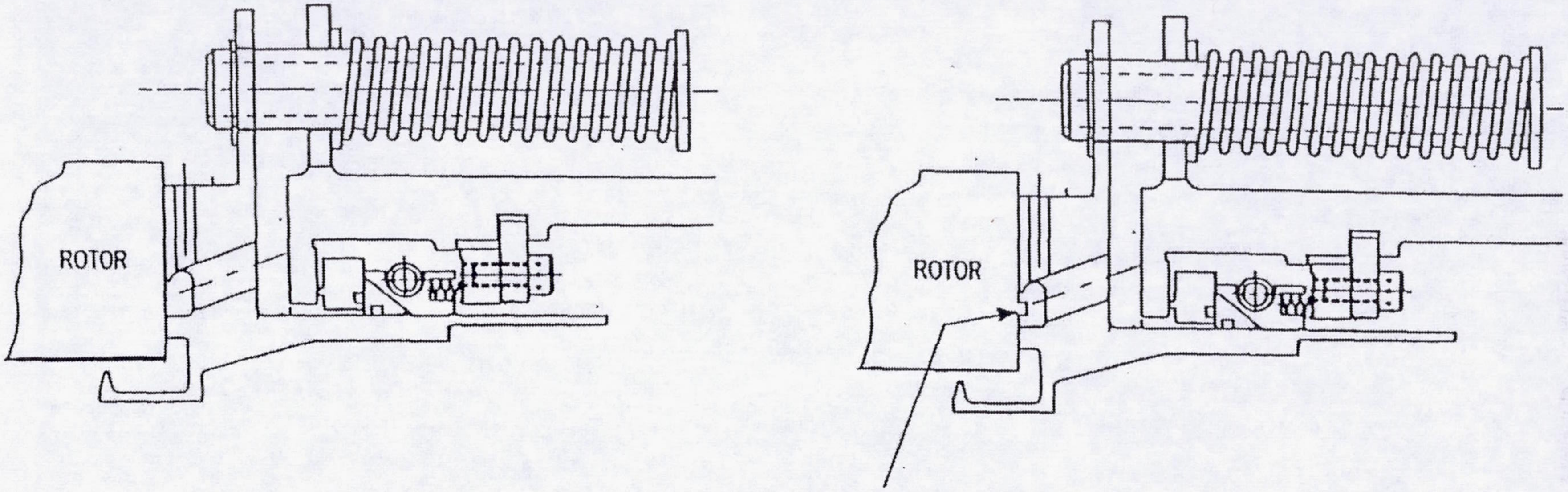
Bearing and dam surface pressure, seal with deflector, 16 mils.



- Without deflector, increased pressure prevents seal closure.
- Deflector reduces pressure in seal/rotor air gap.

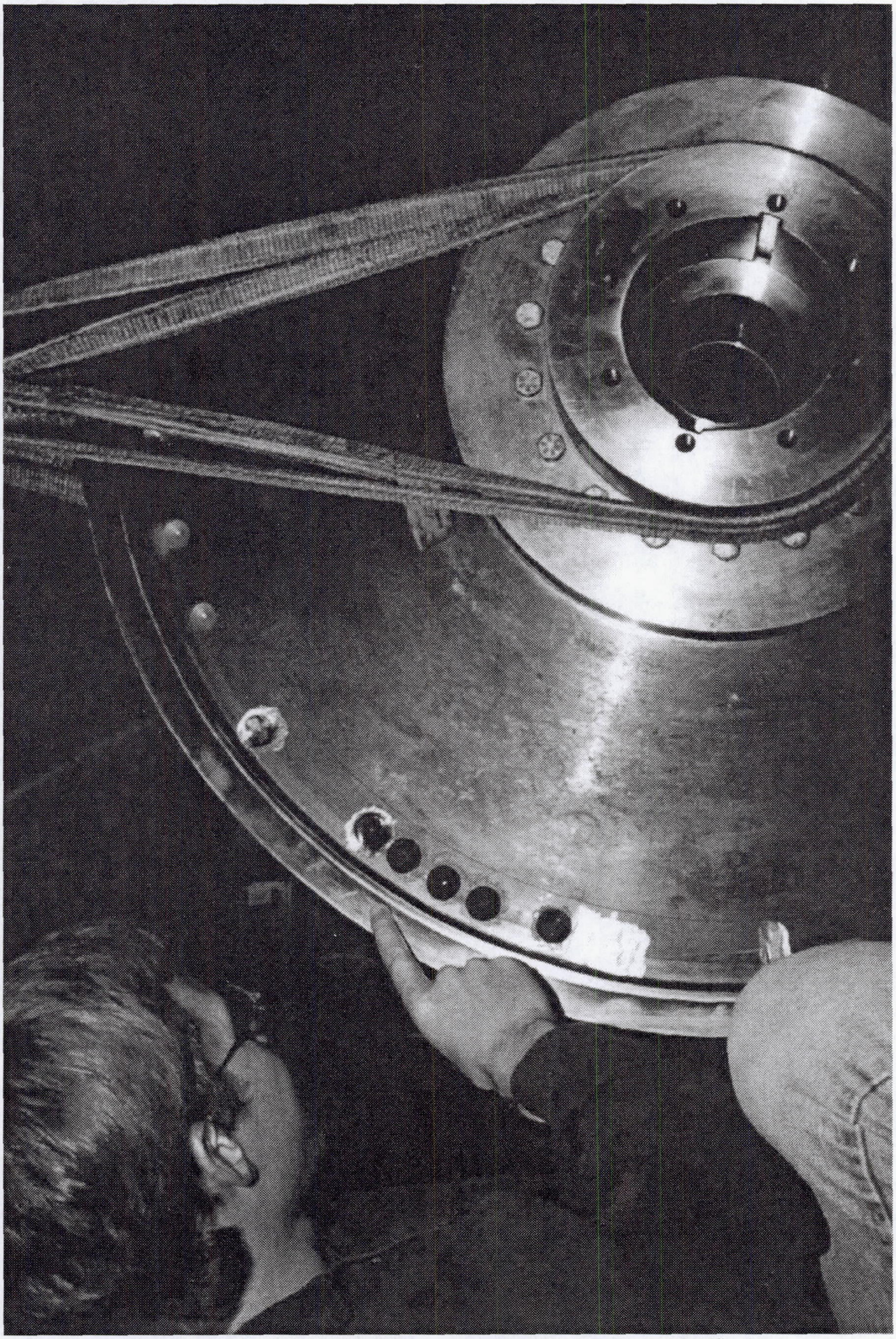
Seal/Rotor Configurations

Original **With Flow Deflector**

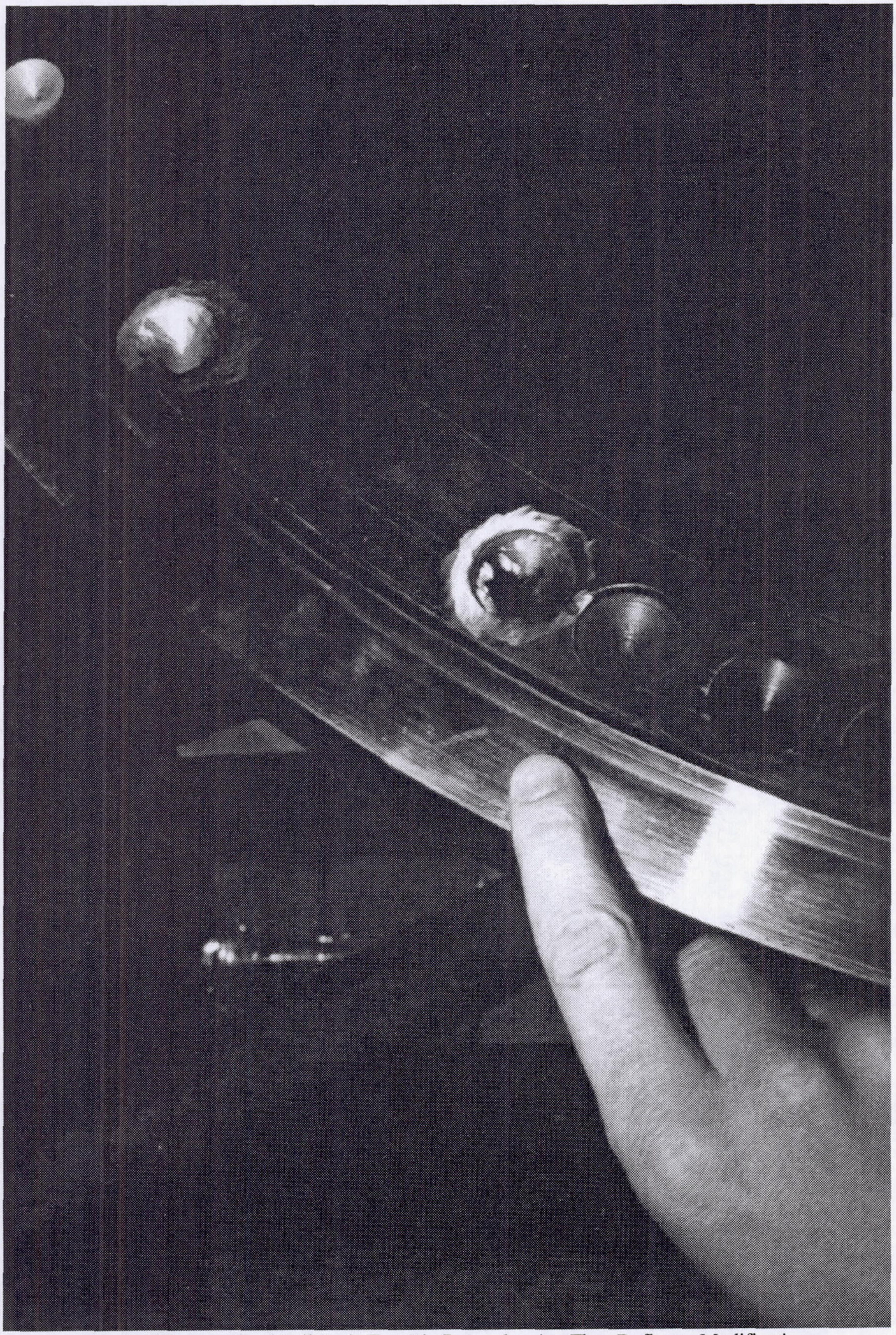


Flow Deflector

• **Flow Deflector machined directly onto rotor surface, radially centered between air dam and air bearing.**



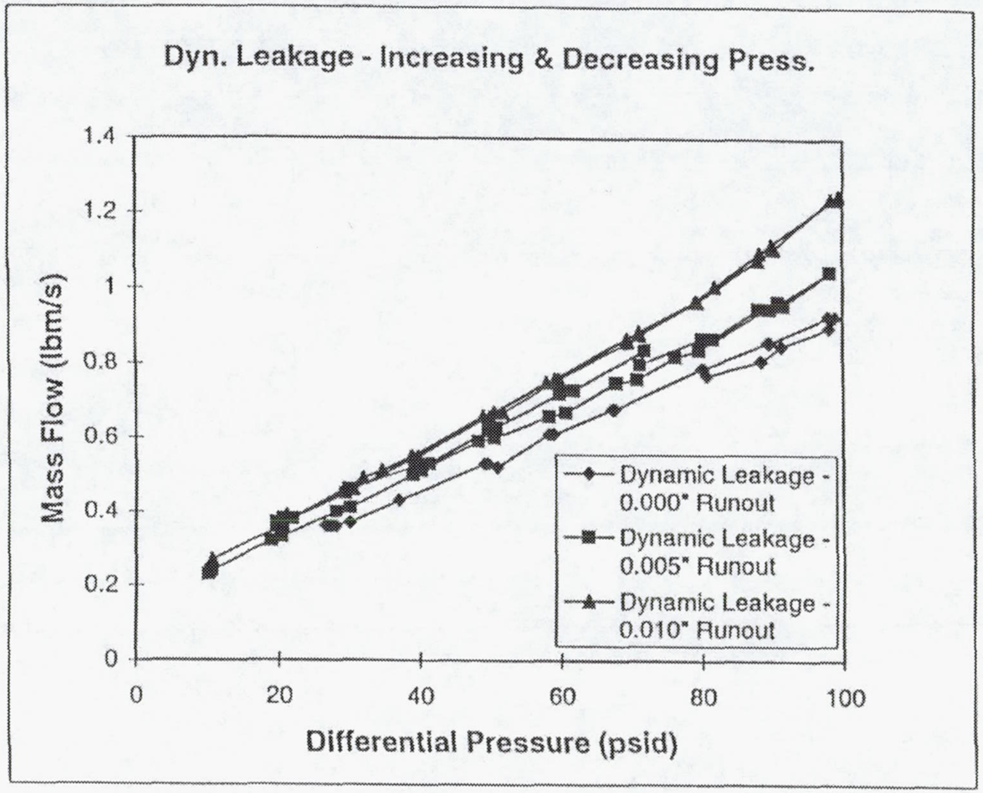
Photograph of Full Scale Test Rig Rotor showing Flow Deflector Modification



Detailed Photograph of Full Scale Test Rig Rotor showing Flow Deflector Modification

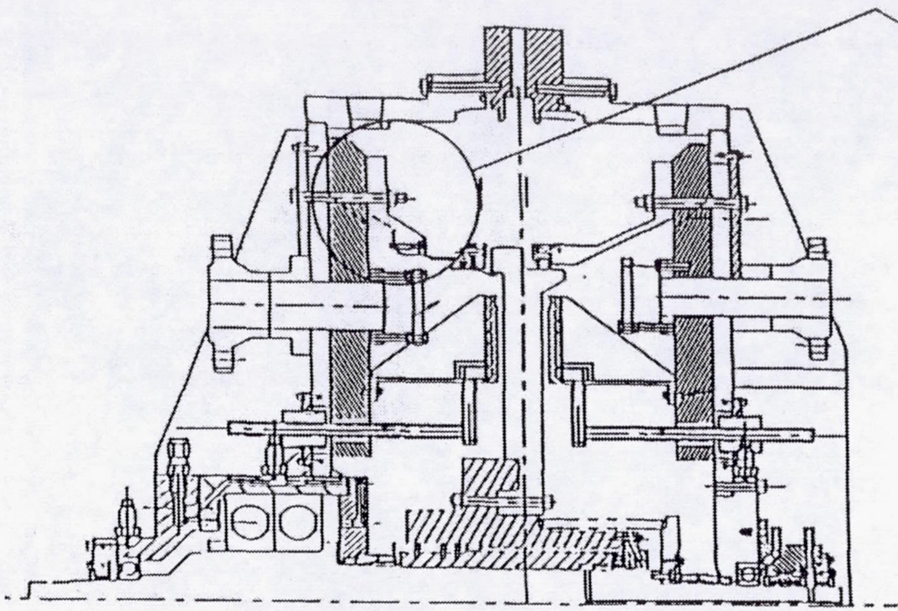
Test Results with Flow Deflector

Dynamic leakage for 0.000'', 0.005", and 0.010" Rotor TIR.

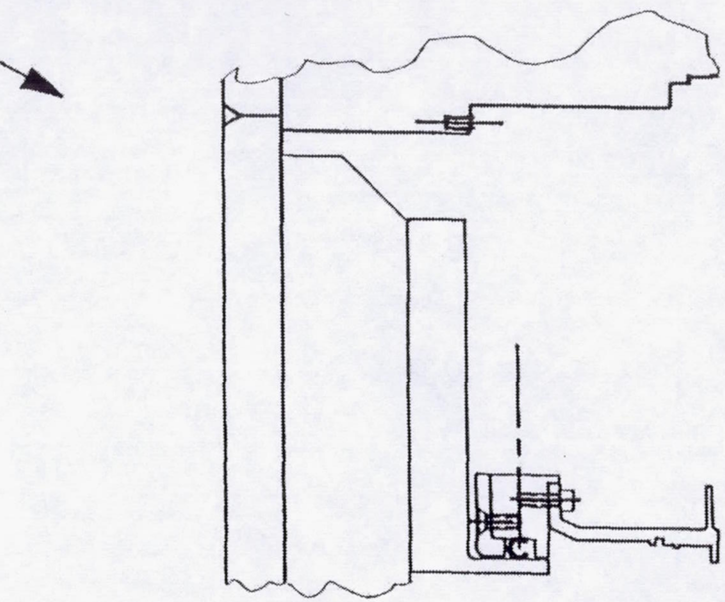


- Seal closure occurs at 2-3 psid for all cases.

Test Rig Modification - Seal Tilt Mechanism

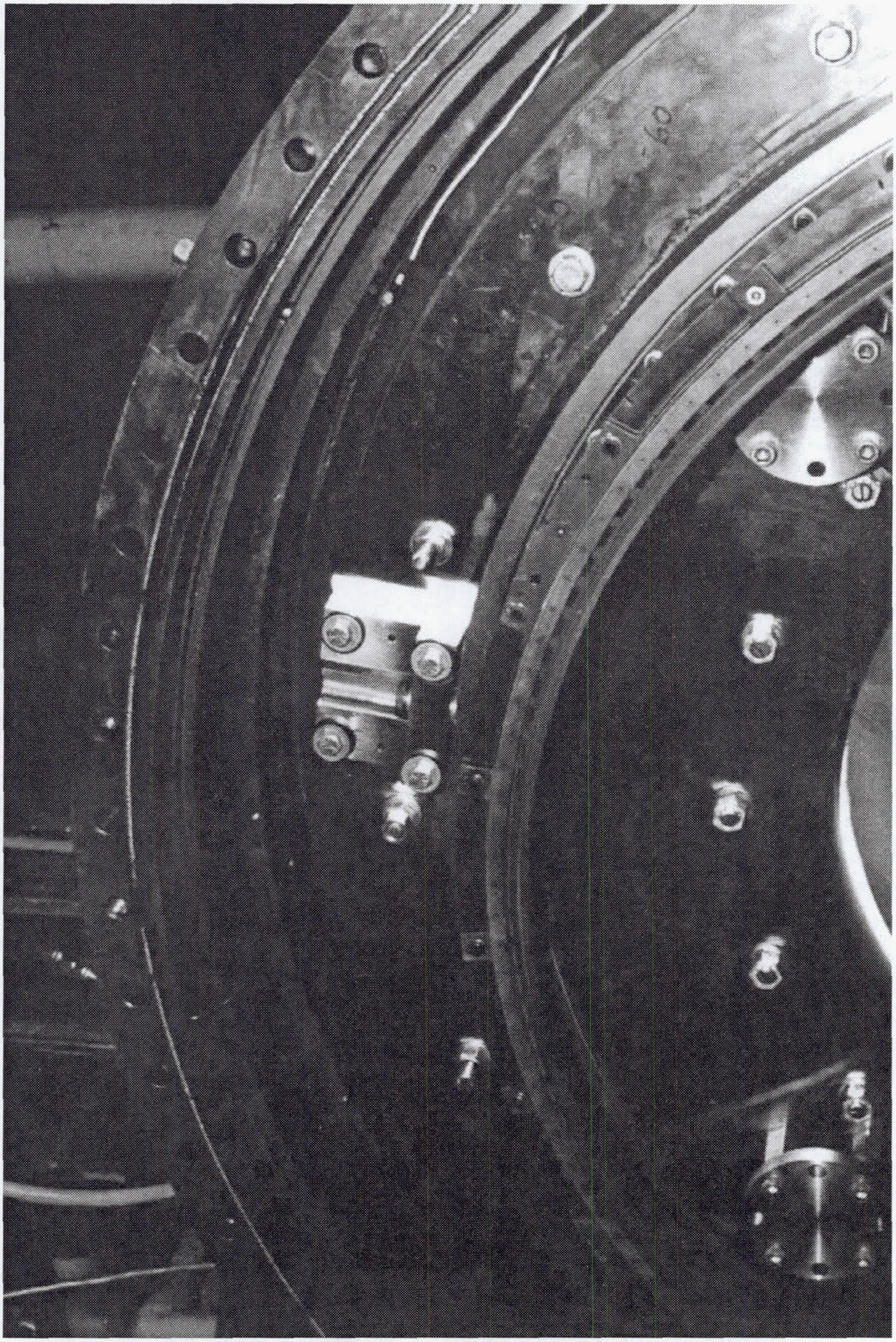


Standard Configuration



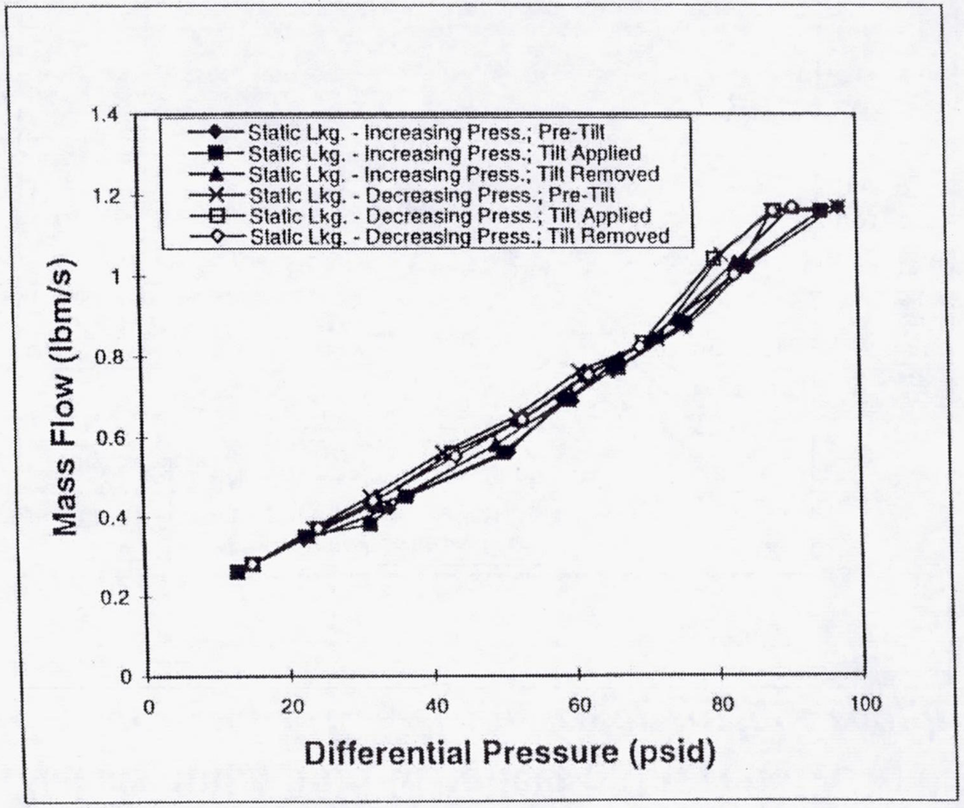
Tilt Mechanism Details

- Seal mounting ring pivots at two locations
- Linear actuators act out-of-phase to tilt ring
- Tilt = 0°- 0.27°- 0° in 0.8 seconds


Photograph of Tilt Mechanism Pivot and Seal Holder with Aspirating Seal Installed

Test Results - Static Leakage with Tilt

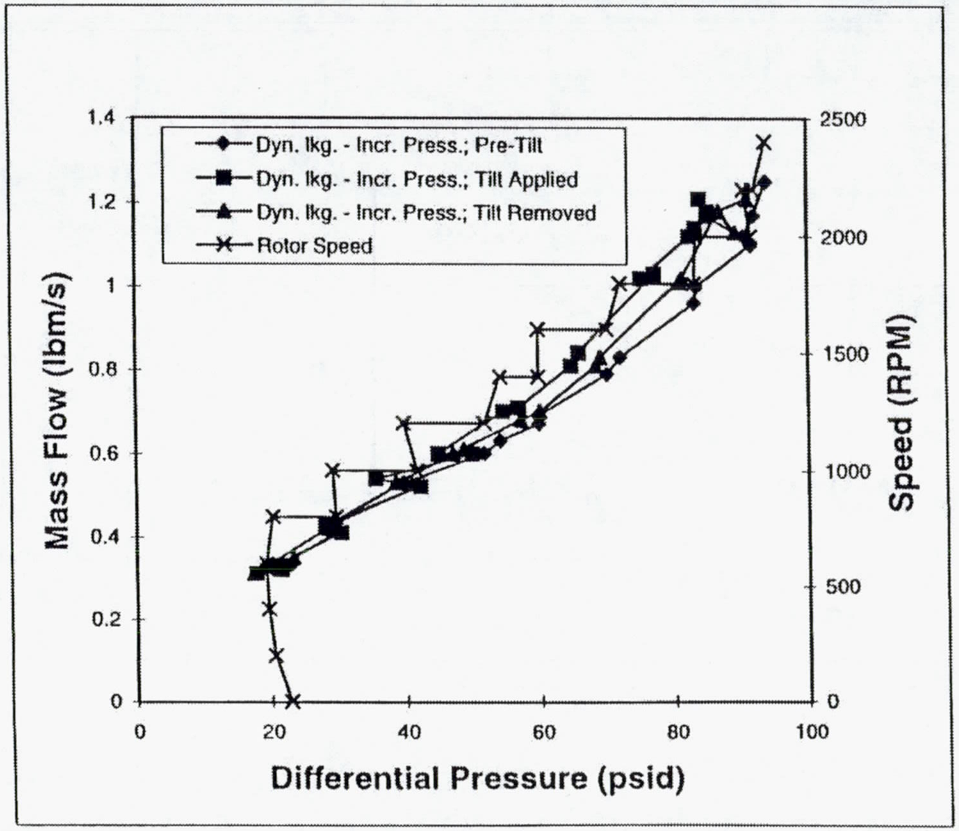
Tilt 0.27° in 0.4 seconds, hold to collect data, remove in 0.4 seconds.
<u>Note</u>: 0.007" rotor axial TIR, 140 µin. rotor surface roughness.



- **At maximum conditions, pressure falls by 6% with tilt while leakage remains essentially constant.**

Test Results - Dynamic Leakage with Tilt

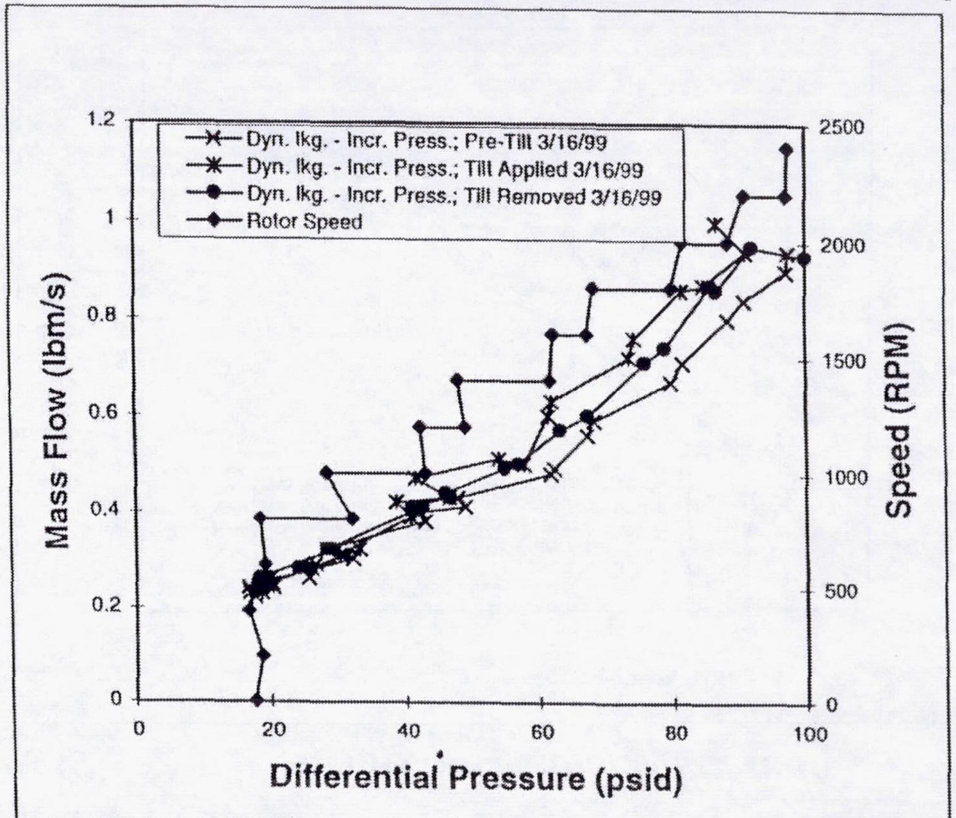
Tilt 0.27° in 0.4 seconds, hold to collect data, remove in 0.4 seconds.
<u>Note</u>: 0.007" rotor axial TIR, 141 μin. rotor surface roughness.



- **At maximum conditions, pressure falls by 10% with tilt while leakage remains essentially constant; recovery is > 95%.**

Test Results - Dynamic Leakage with Tilt

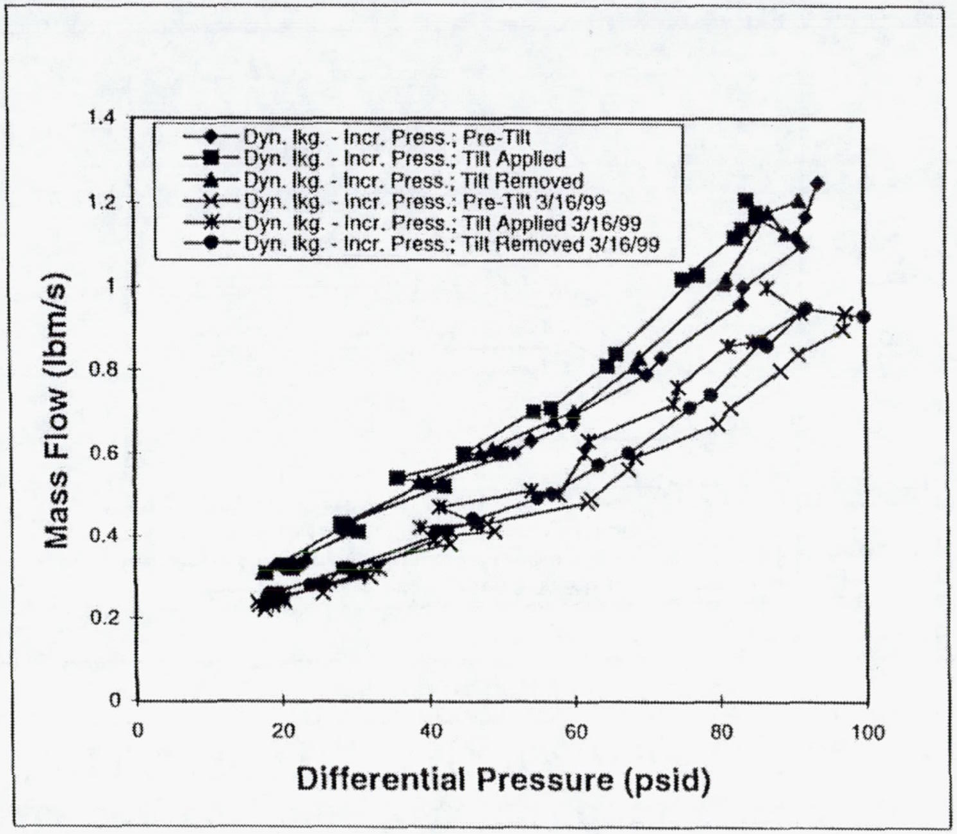
Tilt 0.27° in 0.4 seconds, hold to collect data, remove in 0.4 seconds.
***Note:** 0.007" rotor axial TIR, 13-19 μin. rotor surface roughness.*



- **At maximum conditions, pressure falls by 10% with tilt while leakage remains essentially constant; recovery is > 95%.**

Test Results - Dynamic Leakage with Tilt

Comparison of seal performance with 141 μin. rotor surface roughness and 13-19 μin. rotor surface roughness (03/16/99 data).



- **Seal performance improves by 24% at maximum conditions when rotor surface roughness is improved to 13-19 μin.**

Conclusions

Testing and analysis of the Original and Improved 36” Aspirating Face Seal has revealed the following:

1. Isolation of air flows from the air dam and air bearing regions of the seal is crucial to seal performance.

2. A flow deflector between the air dam and air bearing is effective in isolating flows, allowing a 0.0015” air film to form; for 0.000” TIR, leakage is less than 1 lbm/s at 100 psid.

3. Leakage increases by 17% and 33% for rotor TIR’s of 0.005” and 0.010”, respectively, at 100 psid and 2400 RPM.

4. The aspirating seal can accommodate 0.27° of angular tilt with a performance reduction of approx. 10%. Recovery is 95-100%.

5. A rotor surface roughness of up to 140 μin. can be accommodated, but performance improves by 24% for a roughness of 20 μin.

The aspirating face seal shows promise as a potential replacement for labyrinth seals in aircraft engine applications.

Description of Slides

1. Title slide
2. Objectives and Motivation for Aspirating Face Seal Testing and Analysis
3. Cross-section of the Original 36" Diameter Aspirating Face Seal, showing seal components
4. The Aspirating Seal Test Plan
5. Cross-section of the Full Scale Test Rig, in the Fully Assembled and Open Vessel Configurations
6. Photograph of the Open Full Scale Test Rig with the Aspirating Seal Installed
7. Detailed Photograph of the Aspirating Seal showing the Air Bearing Face and Orifice Holes
8. Photograph of the Aspirating Seal Installed in the Full Scale Test Rig showing Axial Contact Probe
9. Photograph of the Full Scale Test Rig Rotor
10. Wire Frame of the 3-D CFD Model
11. CFD Results - Flow fields for Original Configuration and Improved Configuration with Flow Deflector; both for measured 0.016" seal/rotor air gap at 7.1 psid
12. CFD Results - Pressure Distributions for Original Configuration and Improved Configuration with Flow Deflector; both for measured 0.016" seal/rotor air gap at 7.1 psid
13. Seal/Rotor Cross-sections; Original Configuration and Improved Design with Flow Deflector
14. Photograph of Full Scale Test Rig Rotor showing Flow Deflector Modification
15. Detailed Photograph of Full Scale Test Rig Rotor showing Flow Deflector Modification
16. Test Results - Improved Design Dynamic Lkg. vs. Pressure Differential with 0.000", 0.005", and 0.010" Axial Rotor Runout
17. Test Rig Modification - Seal Tilt Mechanism
18. Photograph of Tilt Mechanism Pivot and Seal Holder with Aspirating Seal Installed
19. Test Results – Improved Design Static Lkg. vs. Pressure Differential with Tilt (0.007" TIR, 140μin. Rotor Roughness)
20. Test Results – Improved Design Dynamic Lkg. and Rotor Speed vs. Pressure Differential with Tilt (0.007" TIR, 140 μin. Rotor Roughness)
21. Test Results – Improved Design Dynamic Lkg. and Rotor Speed vs. Pressure Differential with Tilt (0.007" TIR, 13-19 μin. Rotor Roughness)
22. Test Results – Improved Design Dynamic Lkg. vs. Pressure Differential with Tilt (0.007" TIR, 140 μin. and 13-19 μin. Rotor Roughness Cases)
23. Conclusions

GE LOW HYSTERESIS BRUSH SEAL

Tom Tseng
GEAE
Evendale, Ohio

Advanced Subsonic Technology
Propulsion Technology Transfer Workshop

Area of Interest #8 - Seals / Secondary Air Delivery

"Low Hysteresis Brush Seal"

T.W. Tseng
October 28, 1999

NASA/CP—2000-210472/VOL1

Low Hysteresis Brush Seal

- Goal
- Description
- Subscale Verification Test for Seal Selection
- GE90 Engine Demo Results
- Conclusion

NASA/CP—2000-210472/VOL1

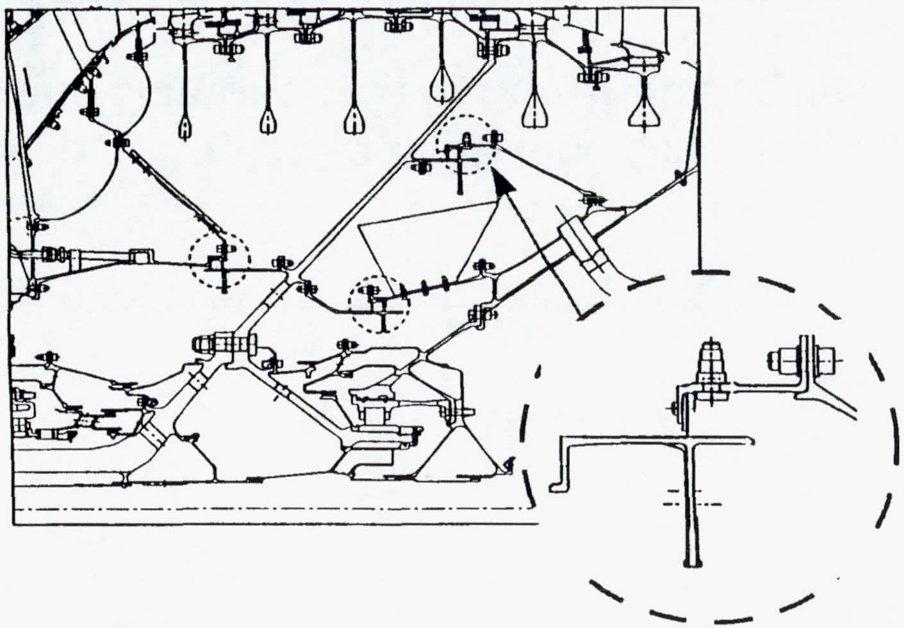
Goal

- **Develop a Single Stage 36-inch Diameter Low Hysteresis Brush Seal and Demonstrate in the GE90 Engine**
  - **Lower Leakage and Better Sealing Retention than the Current GE90 Seal (Goal: 2.6 lb/sec $\geq$ 30% Leakage Reduction @ Worn Seal Condition)**
  - **Relieve Seal Hysteresis at Cruise or Lower Power Setting**

Seal Design Condition

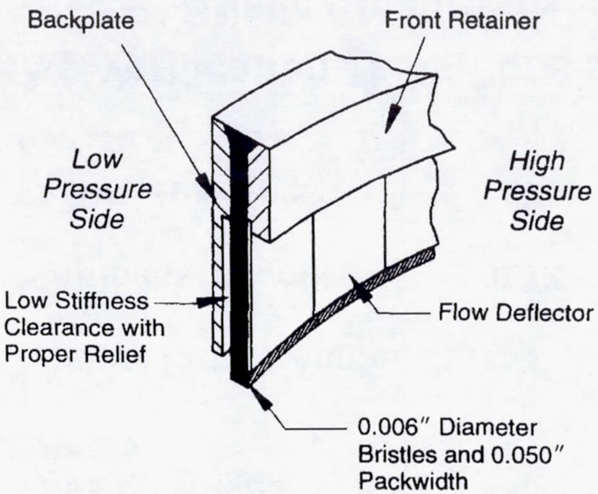
- **Seal Diameter = 36.332 inches**
- **Nominal Operating Condition**

	@ T/O	@ Cruise
Supply Air Temp, °F	**700**	**608**
Cavity Supply Pressure, psia	**120**	**32**
Cavity Exit Pressure, psia	**20**	**6.1**
Rotor Speed, rpm	**2400**	**2254**

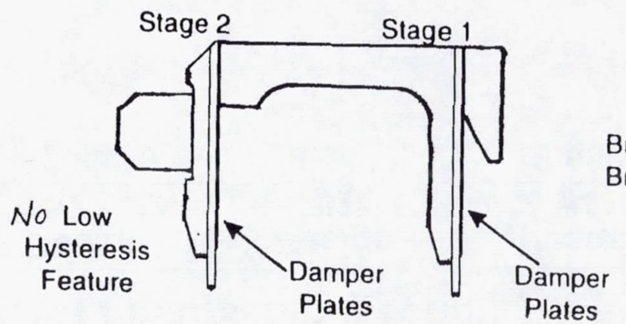


LH Brush Seal

LH Brush Seal Design Features



Current Two Stage Aft Outer Brush Seal



Bristle Diameter: .0027 - .0029
Bristle Lay Angle: 48°

Subscale Verification Tests

- **Five Seals Designed and Tested for Final Seal Selection**

Feature	Design #1	Design #2	Design #3	Design #4	Design #5
Inner Diameter	8.64”	8.64”	8.64”	8.60”	8.60”
Design Bristle Angle	50°	50°	45°	50°	45°
Actual Bristle Angle	53°	49°	43°	47°	44°
Stiffness, psi/mil	0.72	0.67	1.08	0.80	0.99
Fence Height	0.075”	0.075”	0.075”	0.095”	0.095”

- **Verification Tests Consisted of:**
  - Bristle Closure
  - High Radial Interference
  - High Radial Offset
  - Cyclic Endurance

Design #2 Was Chosen For GE90 Demo

Engine Test Sequence

- **PHASE I: New 36-inch Single Stage Low Hysteresis Brush Seal Plus used 20-inch Two-stage Brush Seal at the Beginning of Test Program.**

  Test Sequence: Break in → 50 LCF Cycles → One HCF Cycle*
  → 475 LCF Cycles → Test Completed
  (TRT: 244 hrs)

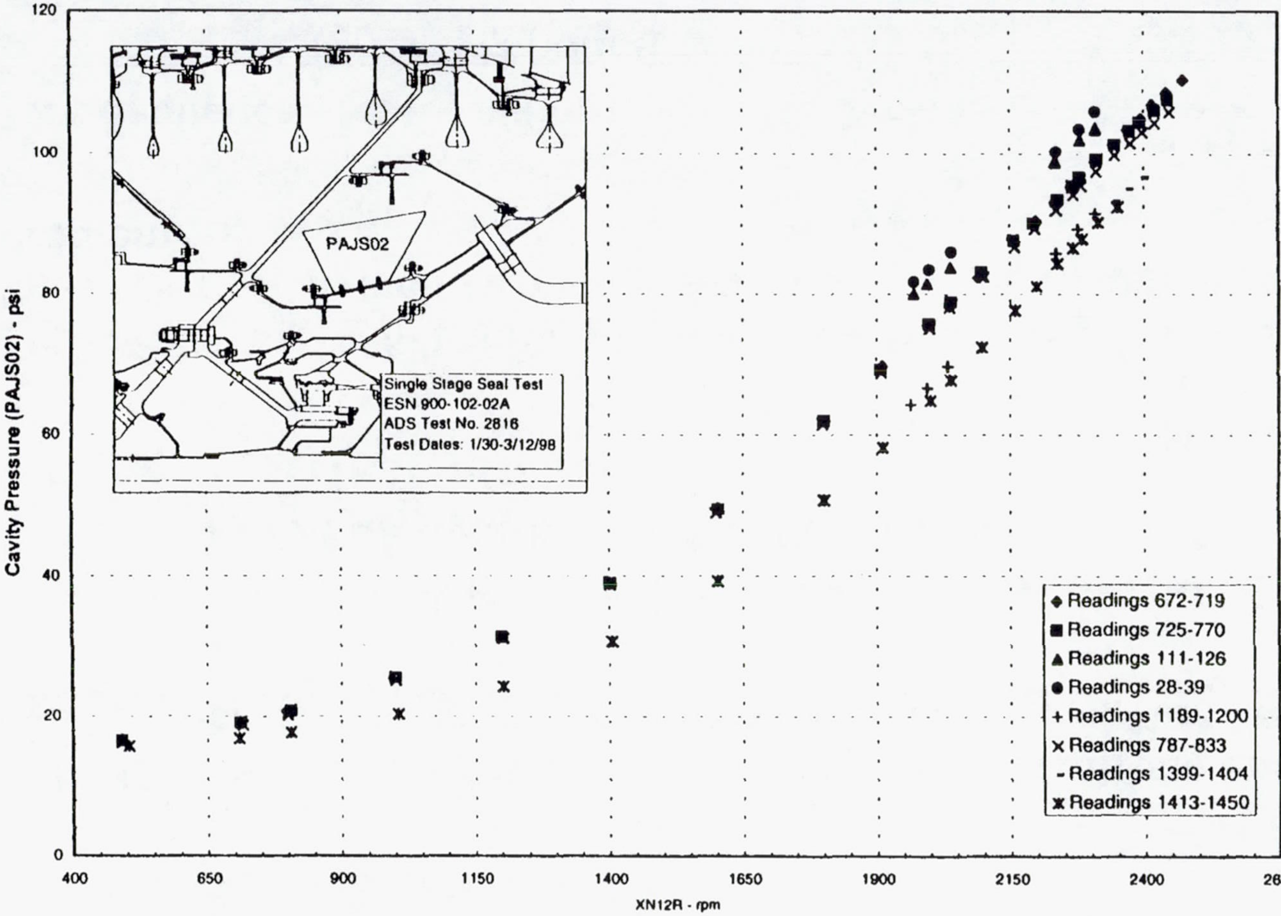
- **PHASE II: Used 36-inch Single Stage Low Hysteresis Brush Seal from Phase I + New 20-inch Two-stage Brush Seal at the Beginning of Test Program.**

  Test Sequence: Ran Additional 774 LCF Cycles
  (TRT: 141 hours)

* **(92 hours Running Time at Large Fan and Core Unbalance; Max 36-inch Seal/Rotor Closure = 15 Mils)**

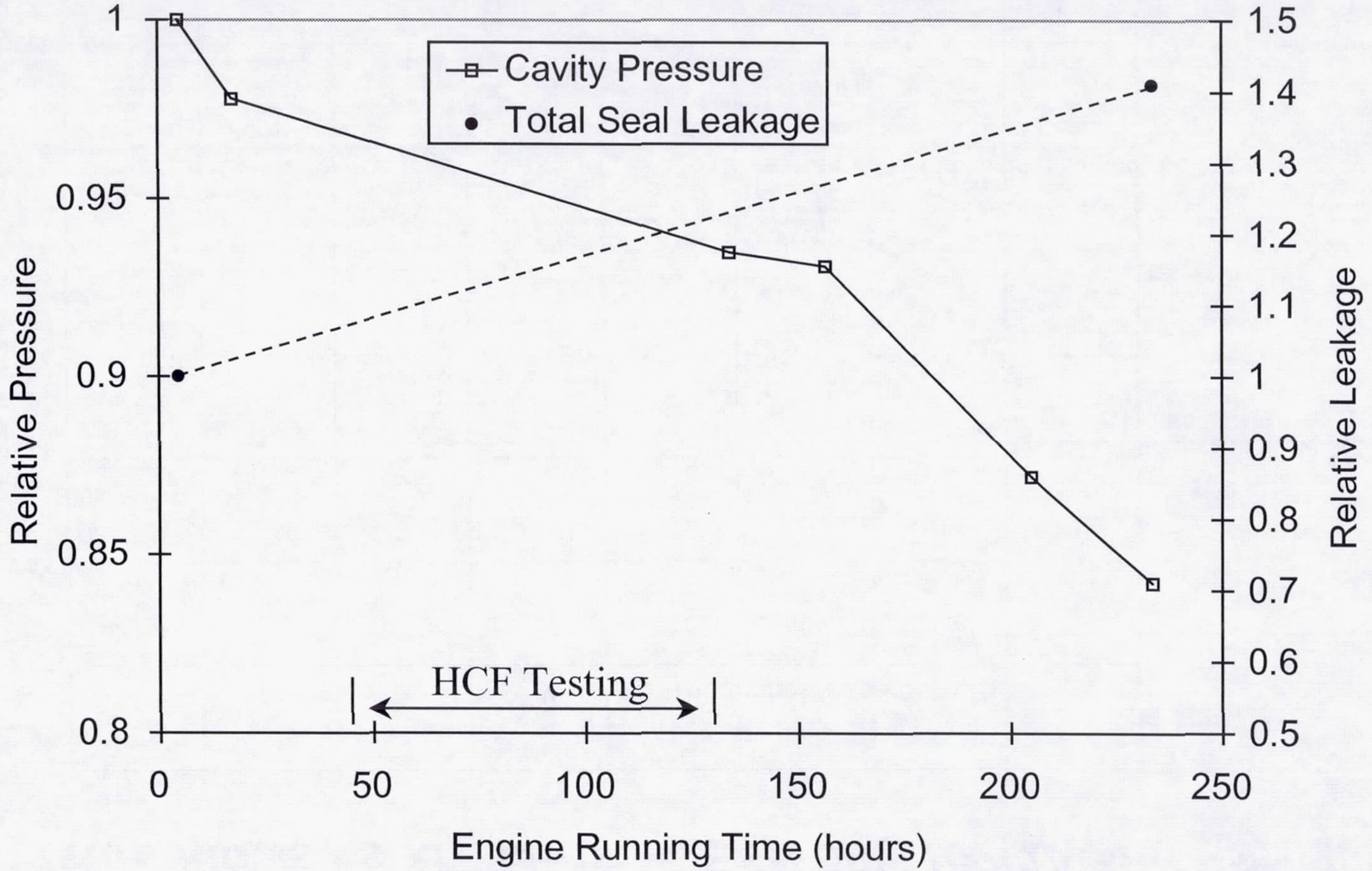
AST Single-Stage Brush Seal Test Results

Thrust Balance Cavity Pressure for Power Cals

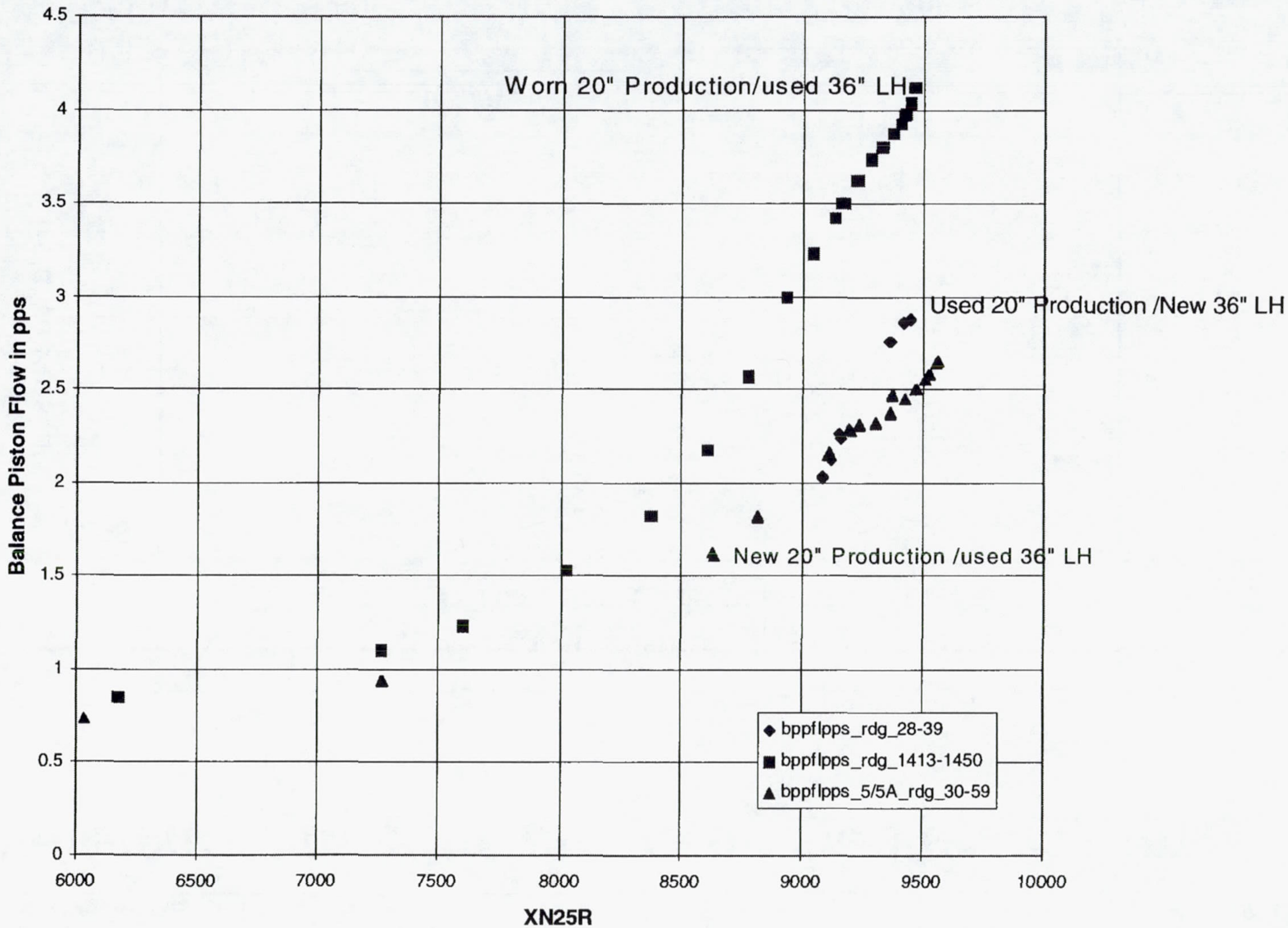


- Cavity Pressures Continue to Drop throughout Testing

Relative Cavity Pressure and Leakage Versus Time



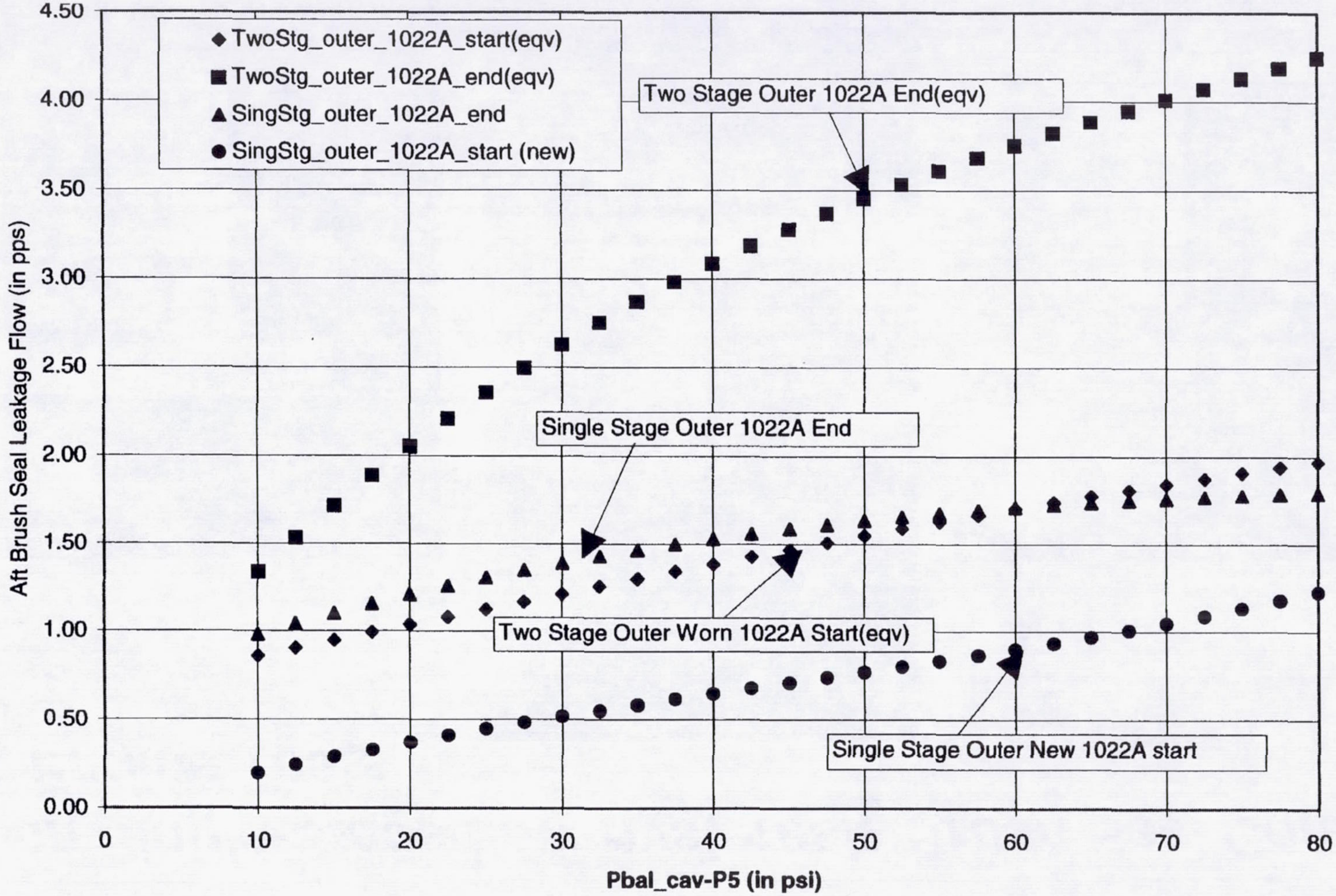
Balance Piston Flows vs XN25R from ESN 900-102/2A and ESN 900-005/5A



AST
Advanced Subsonic Technology

GE Aircraft Engines

Aft Brush Seal Leakage in ESN 900-102/2A at Start and End of Test Program vs (Pbal_cav-P5)



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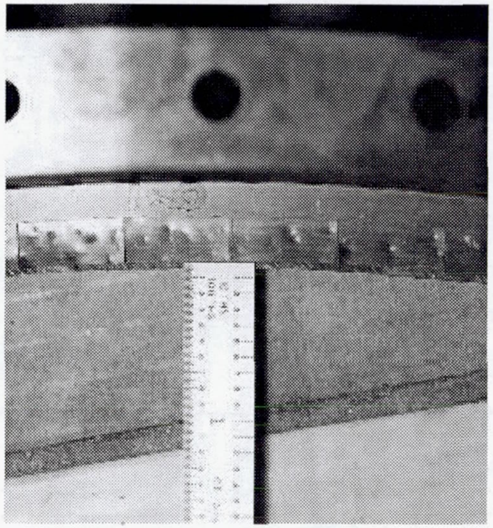
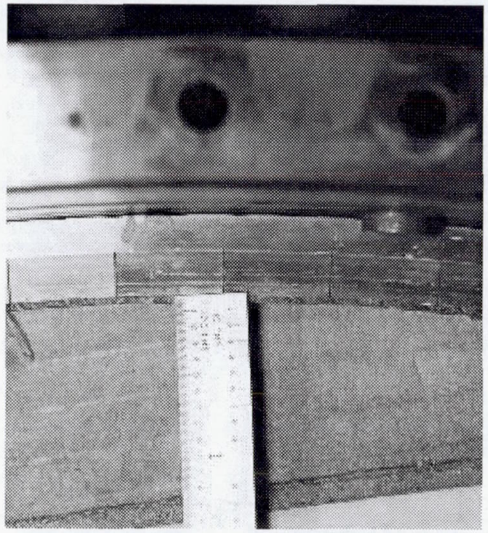
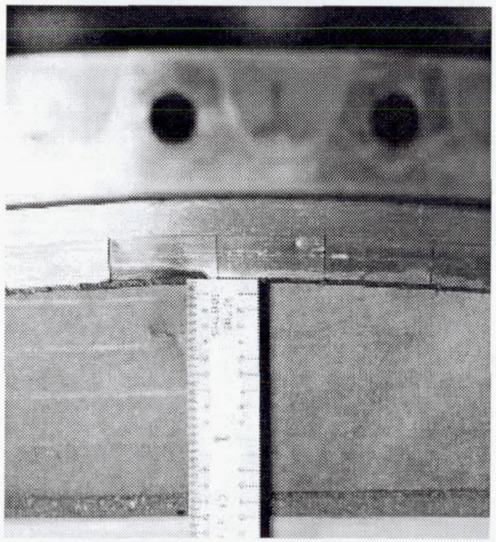
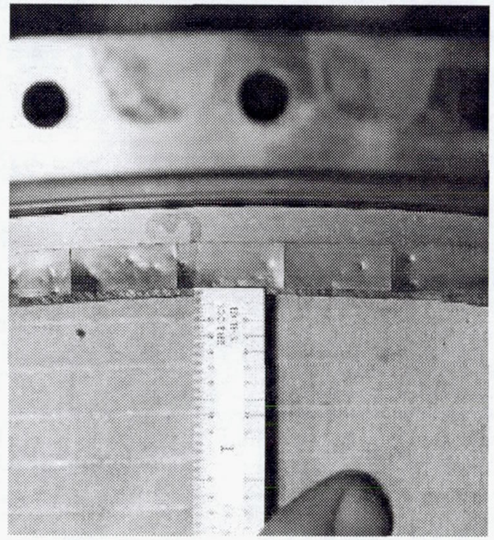
AT(PC)-990911a/11–10/19/2000

36-inch Single-Stage Low Hysteresis Brush Seal Condition After Engine Tests









- Damper Plates were Hit by three Metal Pieces resulting from Baffle Cracks

- No Tufting of Bristles
- Smooth Wear

Conclusions

Single Stage Low Hysteresis Brush Seal Meets Performance and Durability Goals and was Validated for GE90 Engine Application

- **Leakage of the Deteriorated 36-inch Single Stage Low Hysteresis $\leq$ 2.1 lb/sec**
  - **Goal is 2.6 lb/sec**
  - **More than 30% Leakage Reduction over the Current Two-stage Brush Seal**
- **No Tufting of Bristles; Wear was Smooth**

ADVANCED SEALS AT GE RESEARCH AND DEVELOPMENT CENTER

Saim Dinc, Norm Turnquist, and Ray Chupp
General Electric Corporate Research and Development
Niskayuna, New York

Research & Development Center - Advanced Seals

Advanced Seals at GE Research & Development Center

Objective:

Advanced Seals Development, Approach, Methodology, Activities

Overview:

Briefly GE - CRD
Sealing Types Being Developed
Application Areas
Development Approach
DFSS Methodology
Analytical Modeling
Experimental Modeling
Field Validation

GE CRD Advanced Seals Team

- Saim Dinc
- Norm Turnquist
- George Reluzco
- Ming Zhou
- Mahmut Aksit
- Ray Chupp
- Hong Dai
- Jason Mortzhaim
- Hamid Sarshar
- Chuck Wolfe
- Wei-Ming Chi

Presenters

- Saim Dinc
- Norm Turnquist
- Ray Chupp

Advanced Seals at GE Research & Development Center

Type of Seals

Static Seals

- Cloth Seals
- Abradable Seals
- ST Static Seals

Dynamic Seals

- Brush Seals
- Aspirating Seals
- Labby Seals
- Honeycomb Seals

Static Seal Testing

Brush & Cloth Seals
1000 psi
1000F

Dynamic Seal Testing

Brush, Aspirating, HC Seals
36 & 50 in. Dia.
800 ft/sec
100 psi

Dynamic Seal Testing

Brush Seals
1200 psi
1000 F Air & Steam
800 ft/sec

Applications

Gas Turbines

Compressor & Turbine Seals

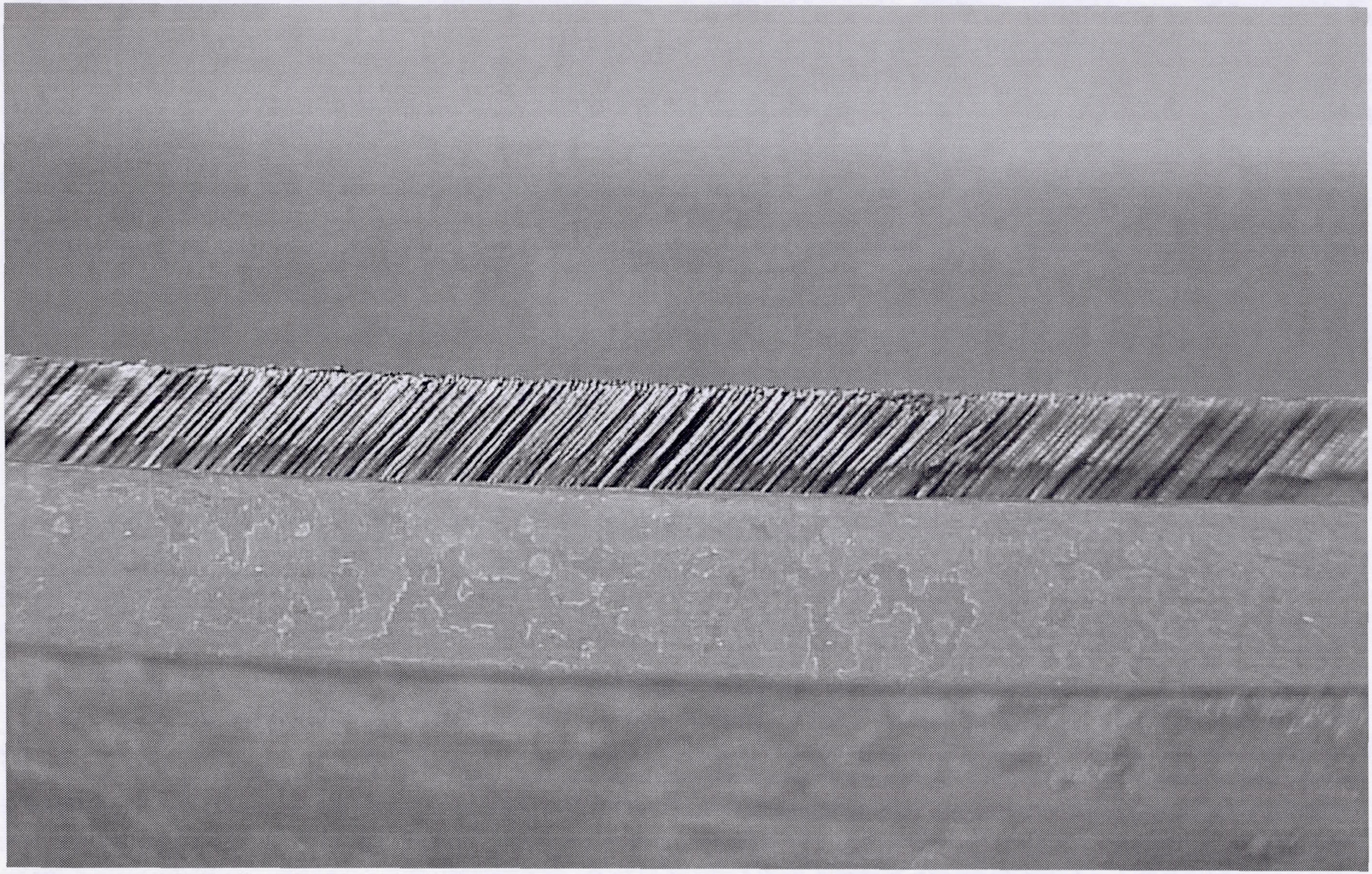
Steam Turbines

Generators

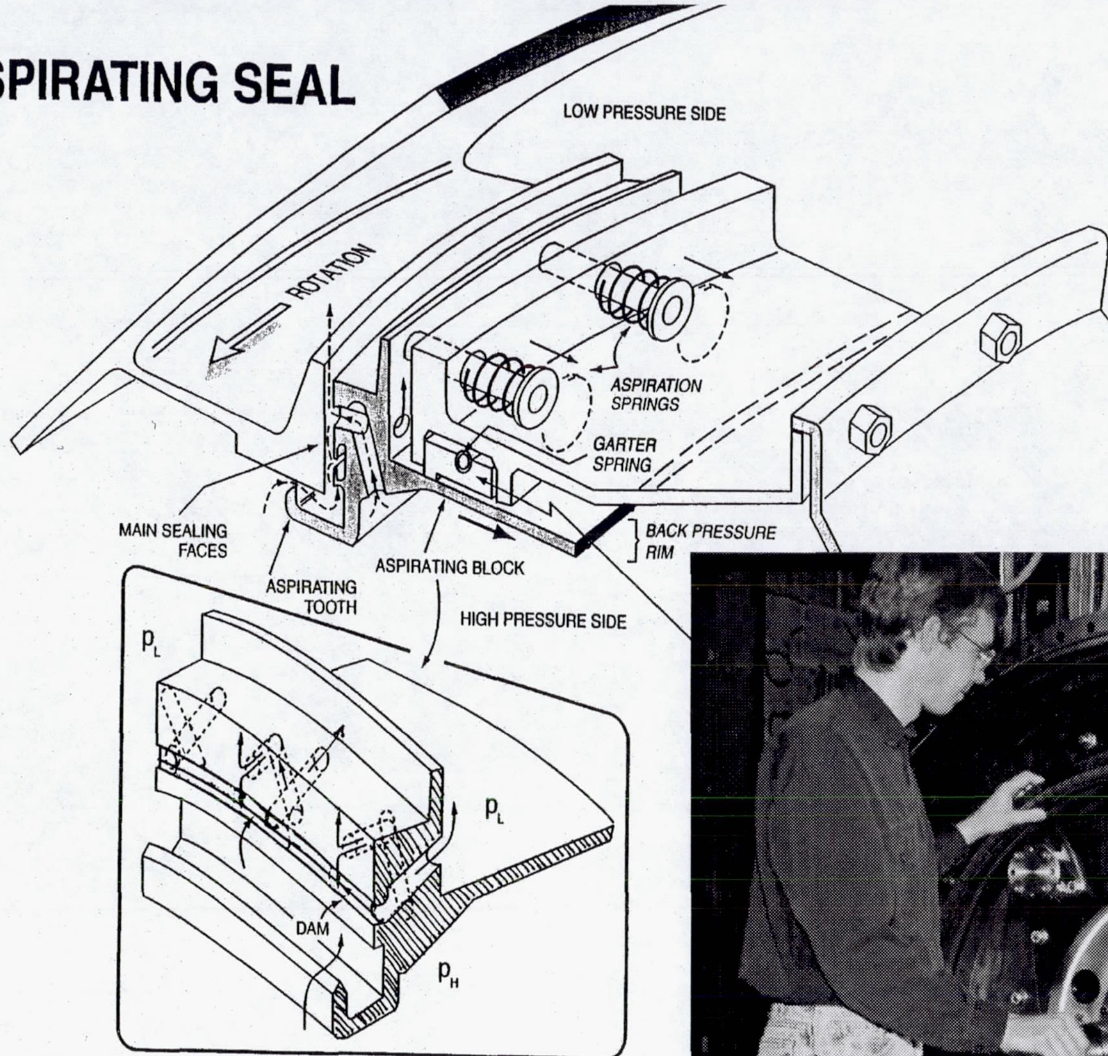
Compressors

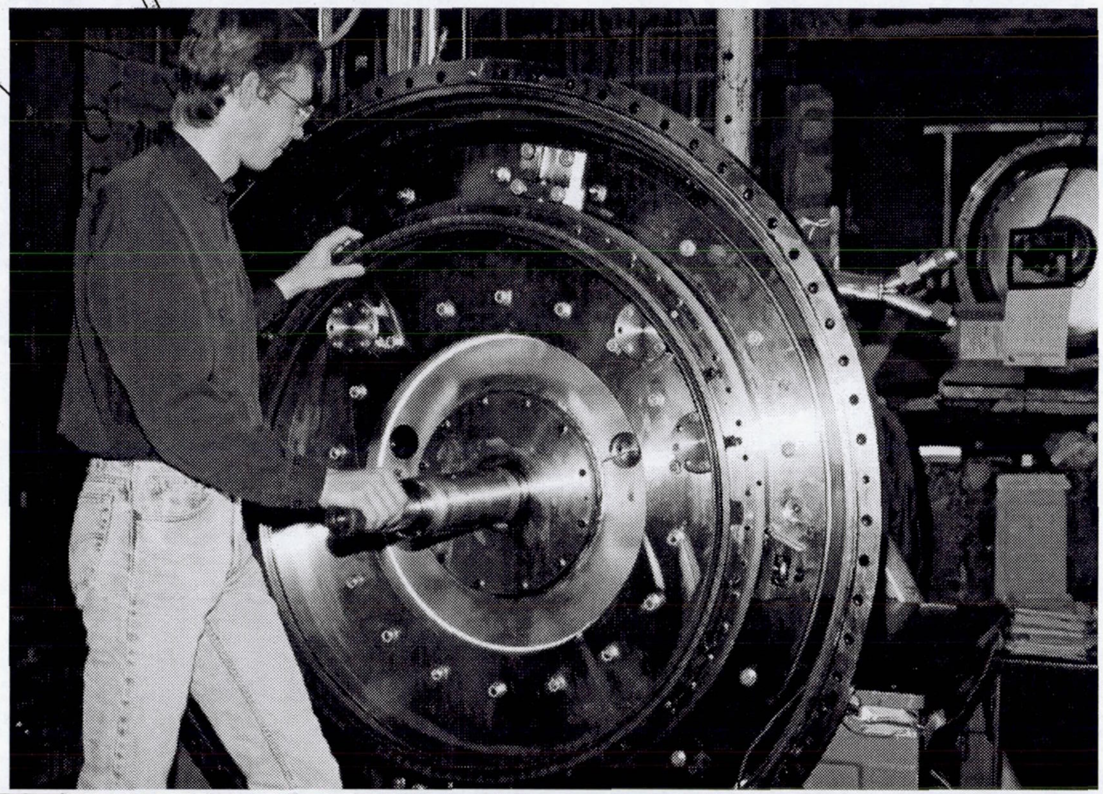
Aircraft Engines

Gas Turbine Brush Seals: After 3 Years of Service



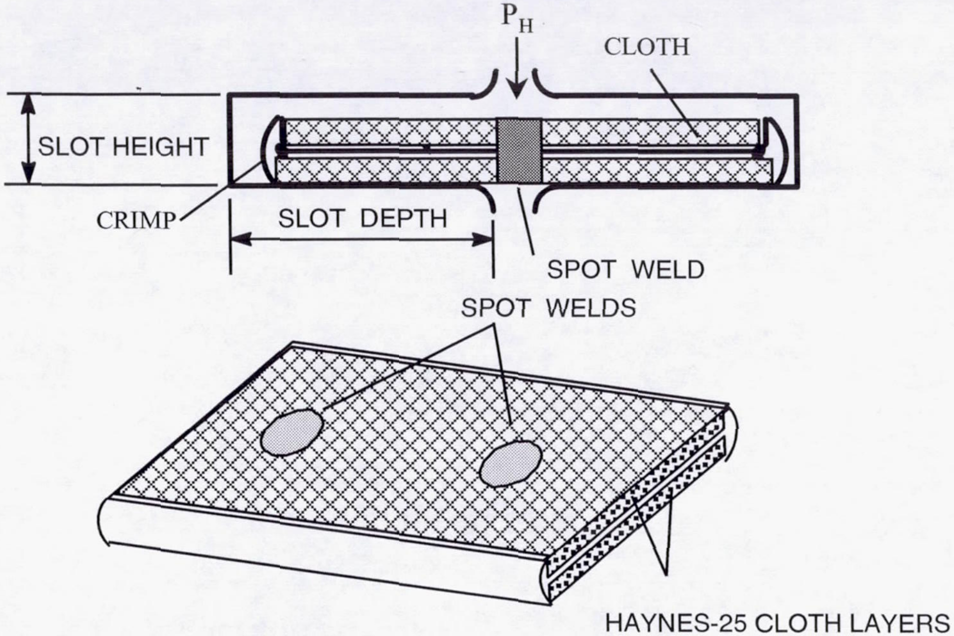
ASPIRATING SEAL



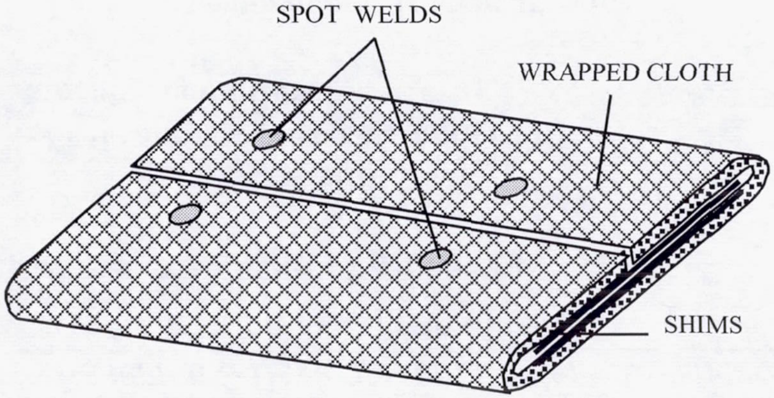


Stationary Seal Applications:

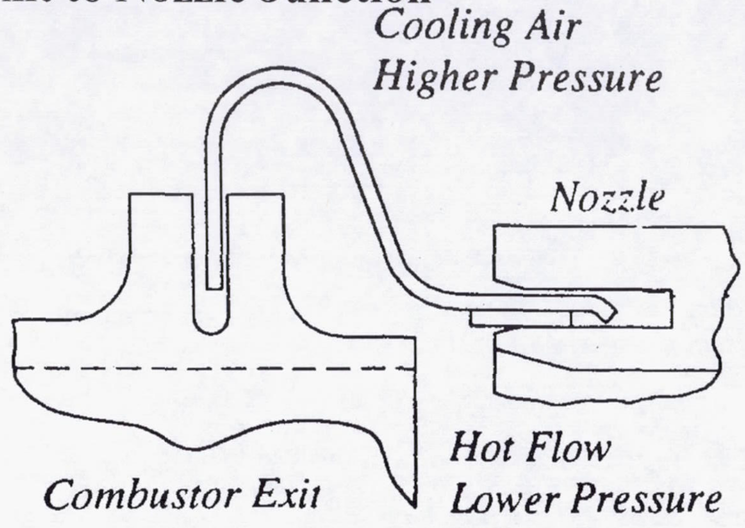
Cloth Seals at Turbine Section Hot Gas Path



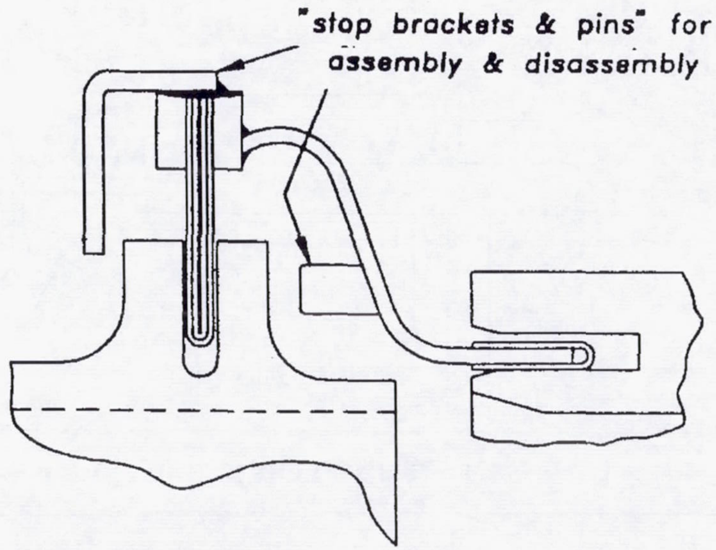
WRAPPED CLOTH SEAL



Cloth Seals at Combustor Exit to Nozzle Junction



(a) Previous sealing arrangement



(b) Sealing arrangement with cloth seals

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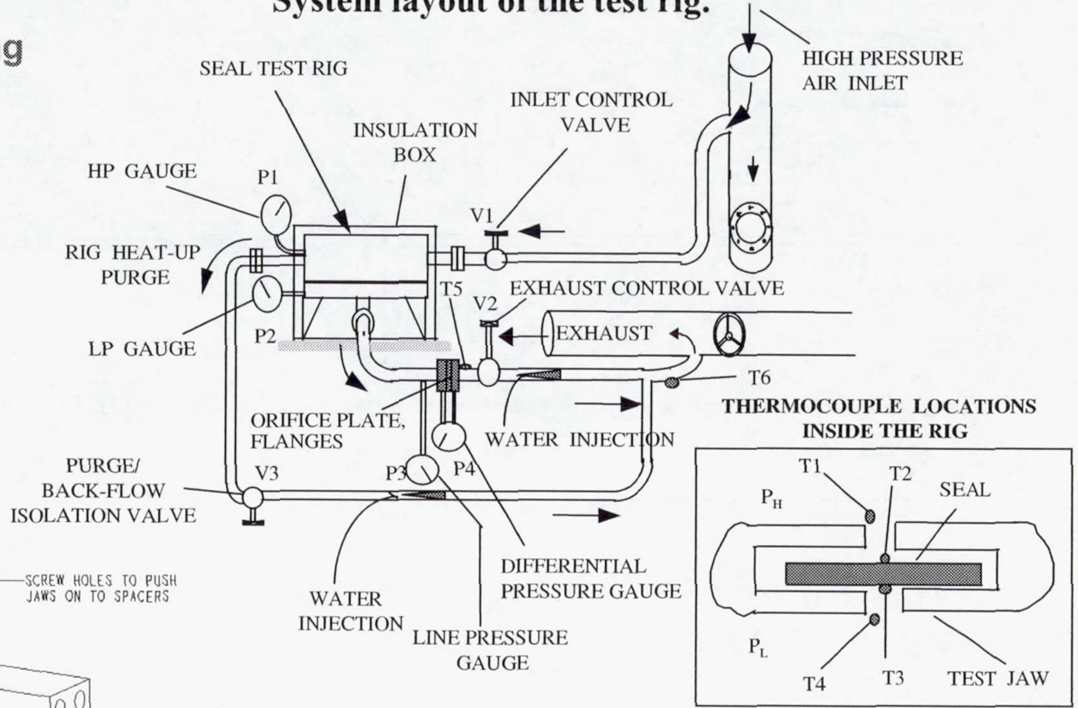
Cloth Seals Leakage Performance Testing

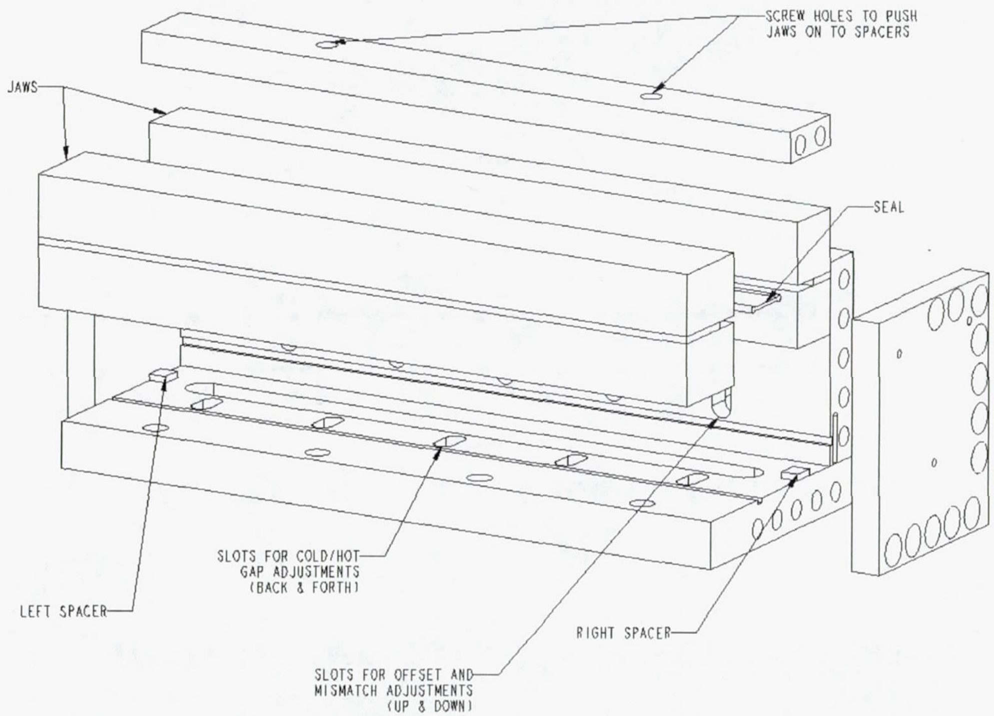
- **Seal samples are tested under different machine conditions.**

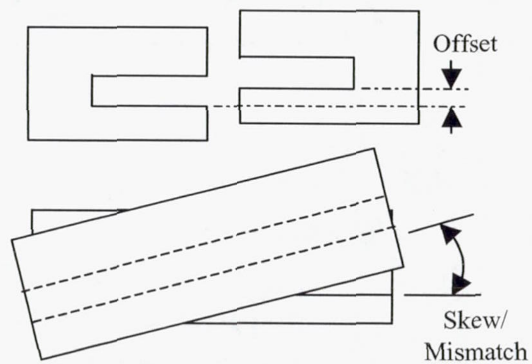
- **Leakage performance is measured for various slot offset, skew, pressure ratio and temperatures.**

System layout of the test rig.



Test sample assembly





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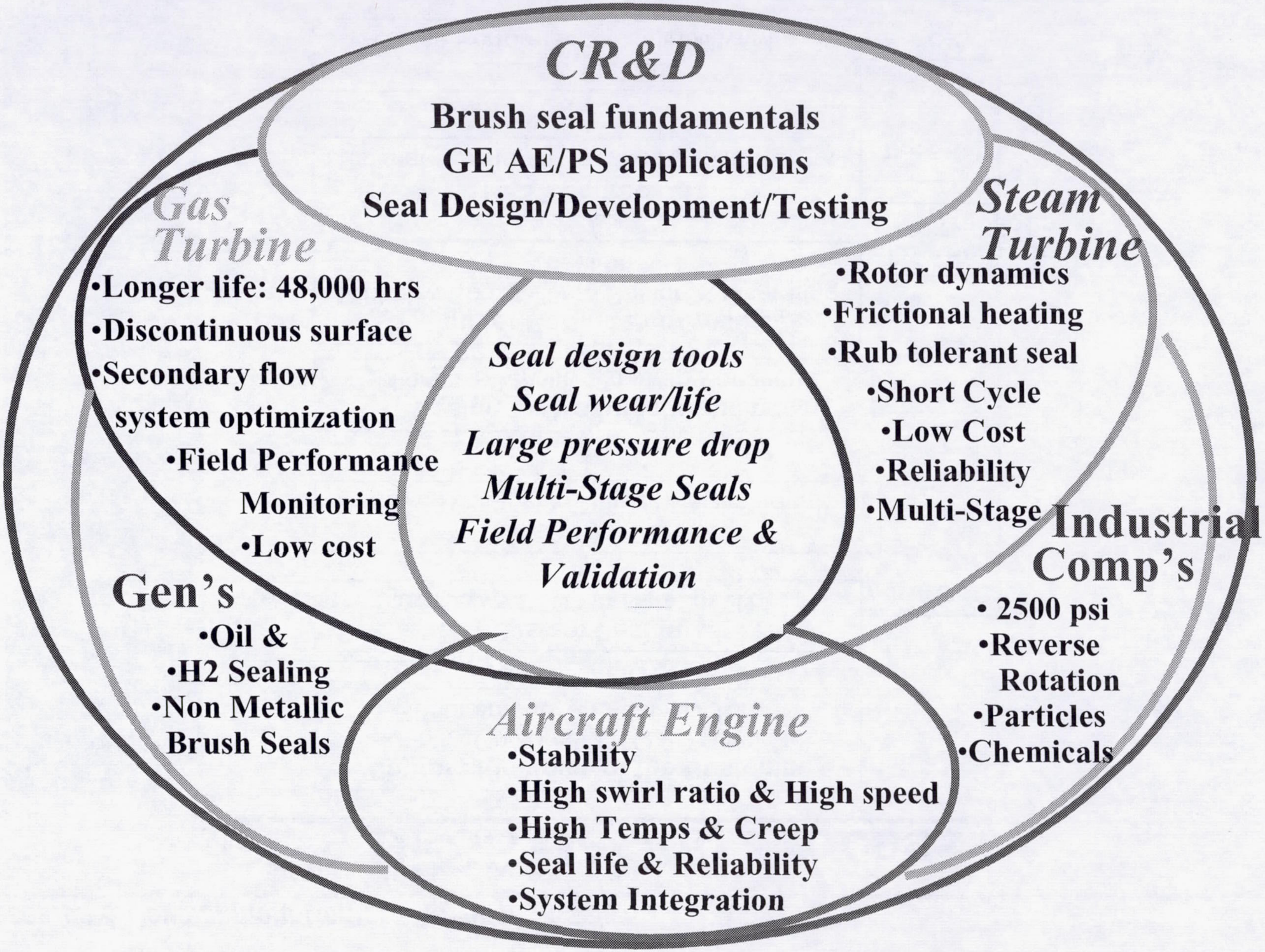
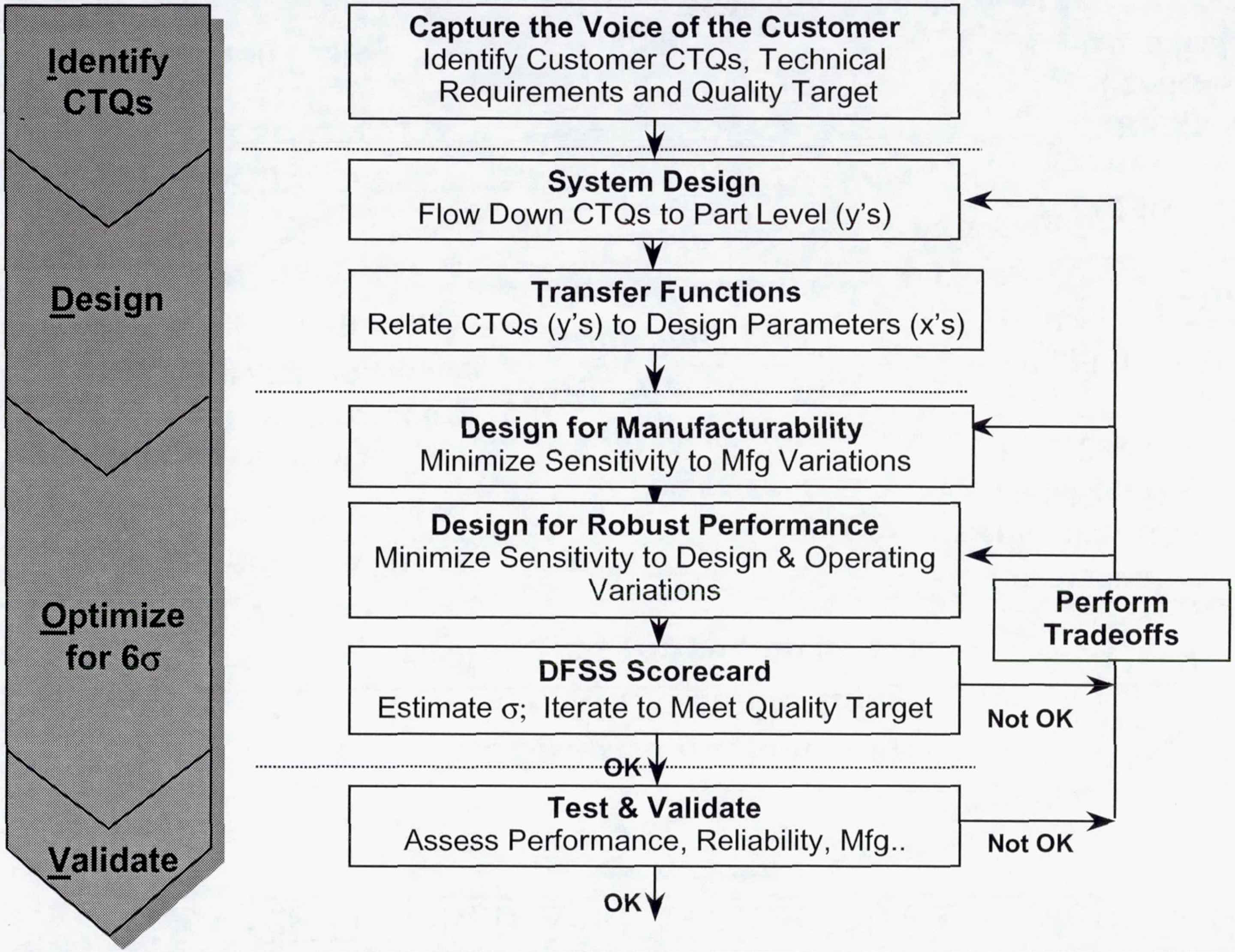
GE - CRD Brush Seal Technology Development

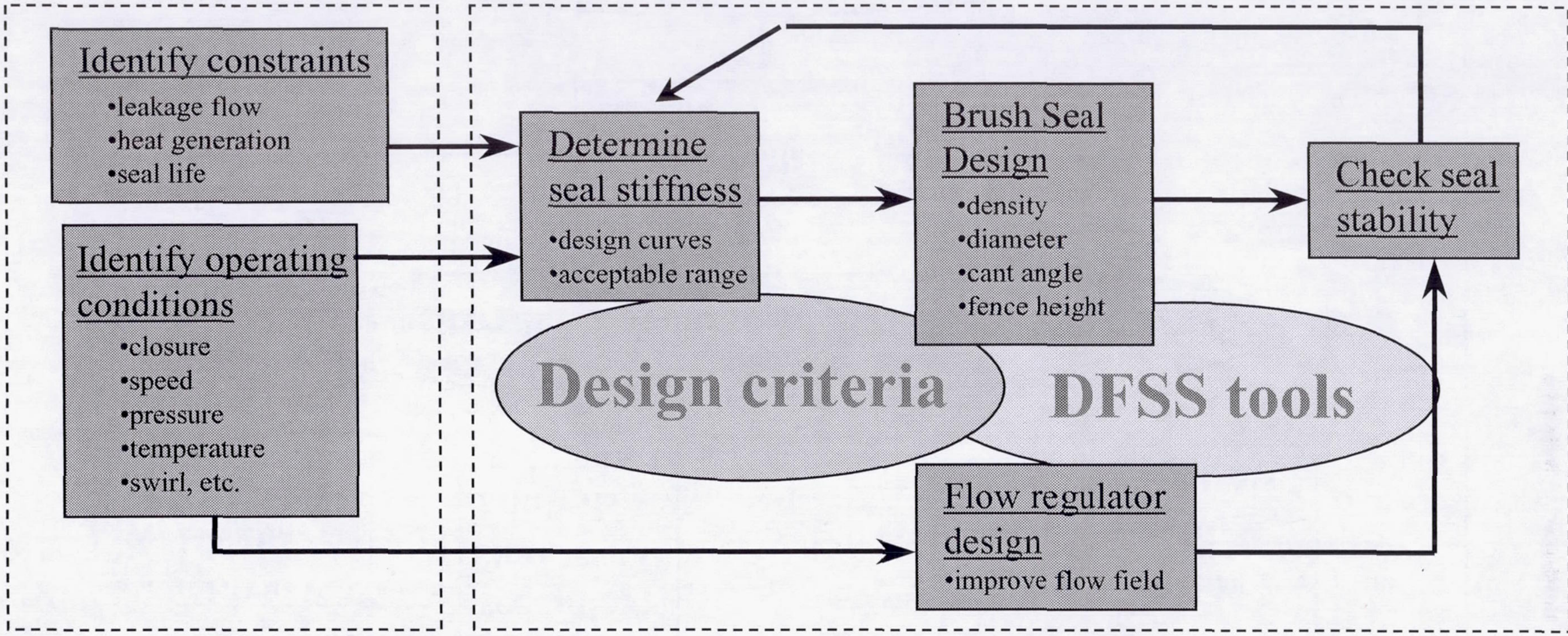


GE's DFSS Design Process



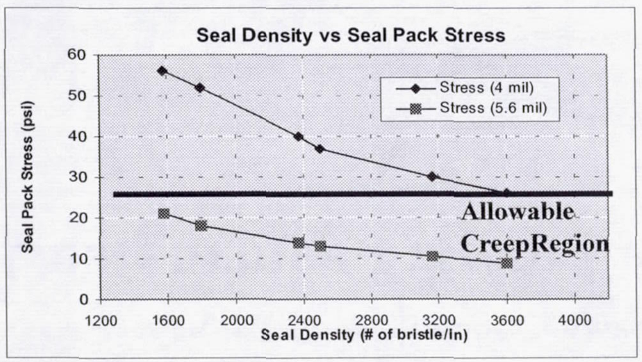
Predictive, statistical design, to achieve 6σ during product development

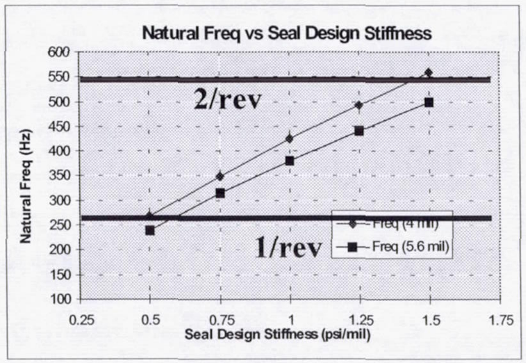
Brush Seal Design Process/Methodology

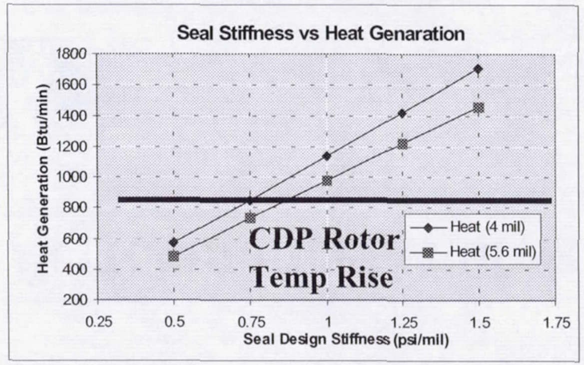


Establish operating conditions **Systematic seal design**

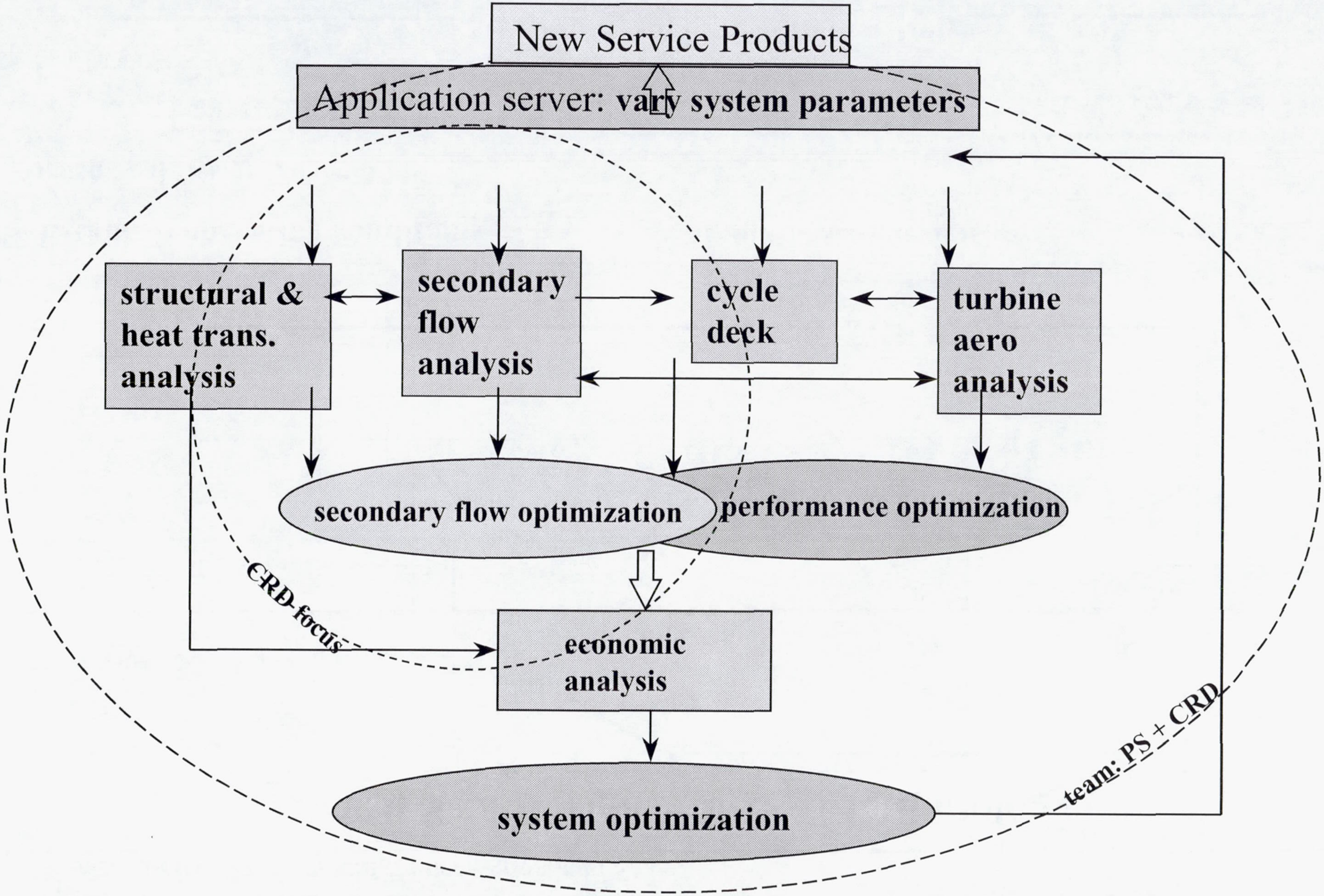
Brush Seal Design Tools:







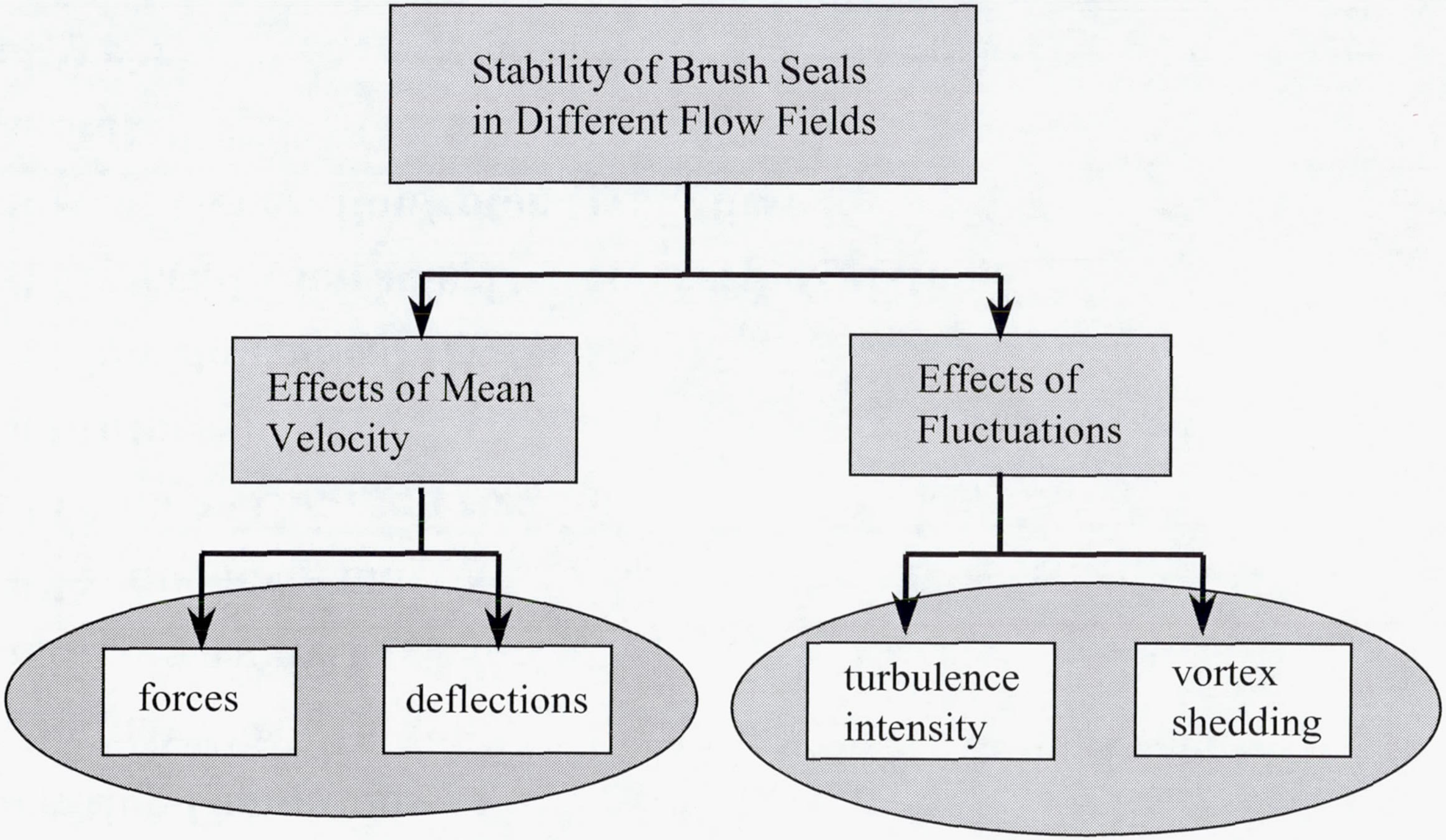
Gas Turbine System Level Secondary Flow/Performance Analysis



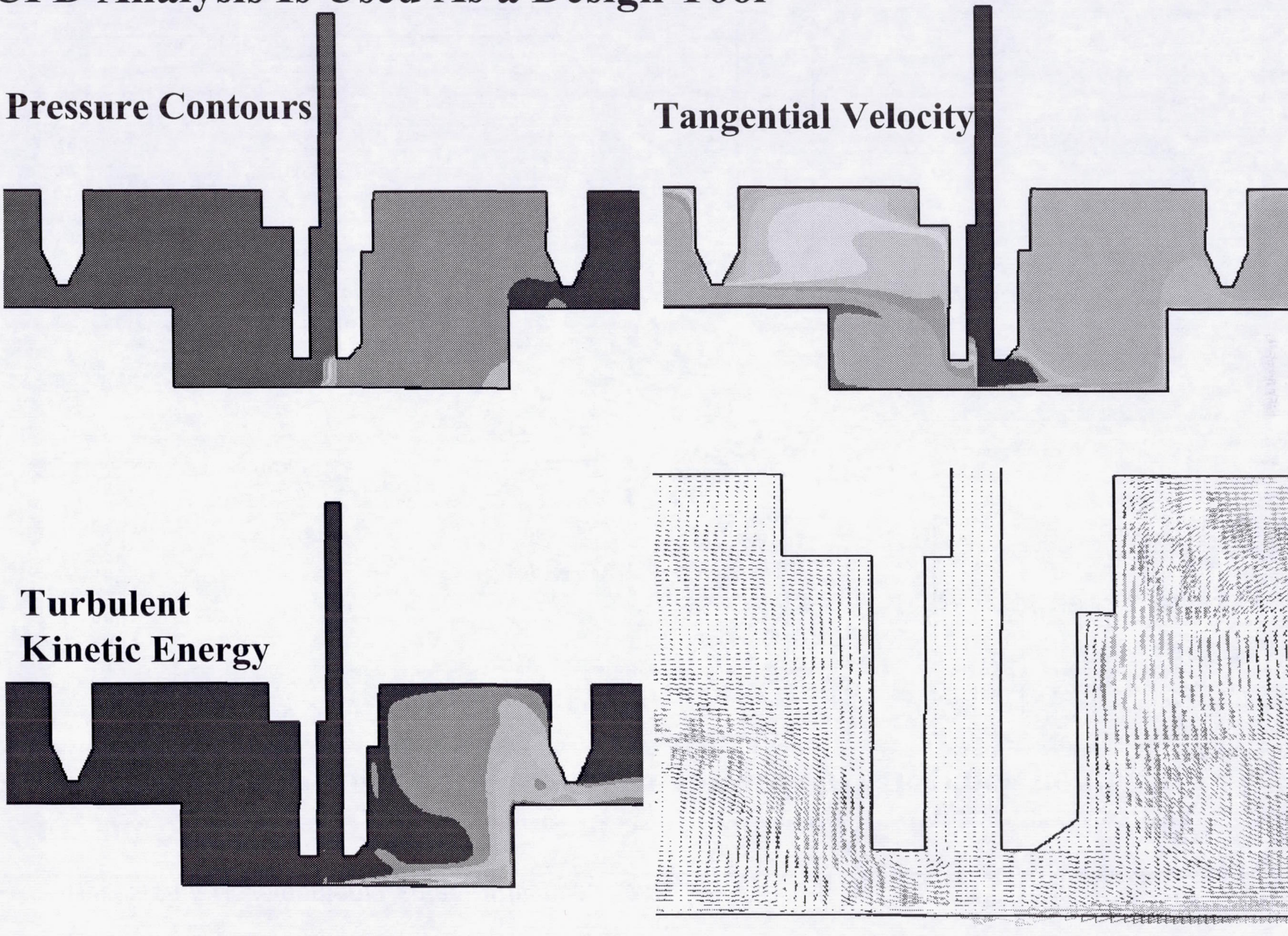
The Approach for Brush Seals Development

- Operating Conditions
- Preliminary Seal Design
- Seal Stress Analysis
- Seal Frequency Analysis
- Seal Leakage Characterization
- Seal Stiffness
- Seal Blow-down/Seal Hysterisis
- Seal Material Characterization/creep/oxidation
- Seal Heat Generation/rotor Dynamics
- Seal Stability
- Seal Wear
- Seal Life/performance Degradation/seal Design for Reliability
- Seal Component & Sub-scale Testing
- Seal Engine Assembly
- Field Performance Test/secondary Flow Optimization
- Design Tools Validation/field Data Integration

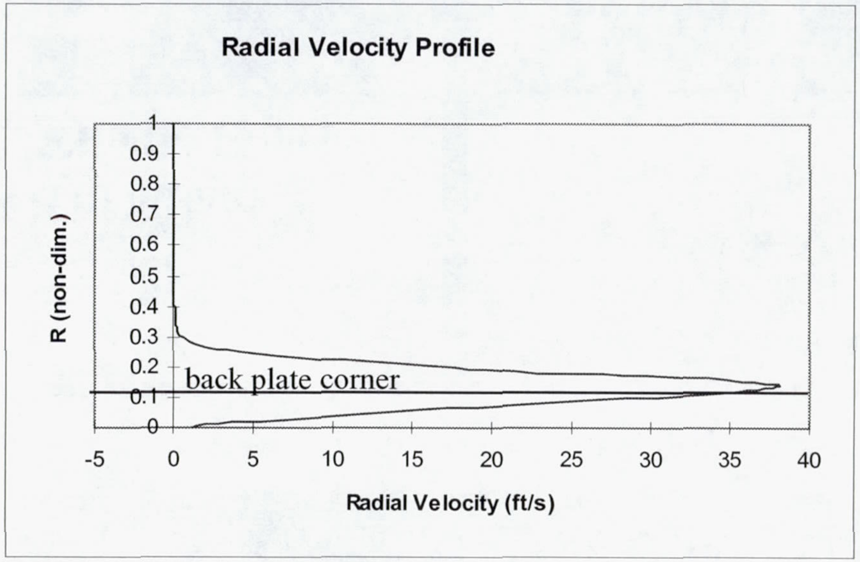
Brush Seal Stability Road Map

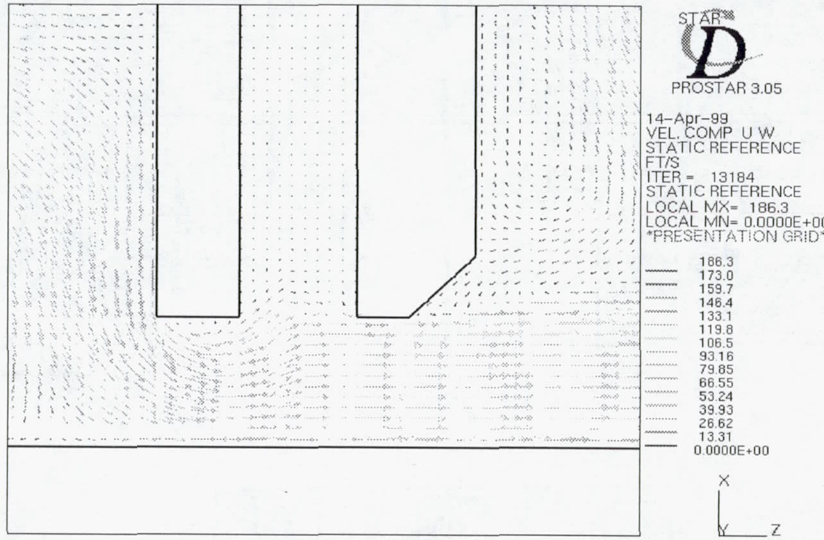


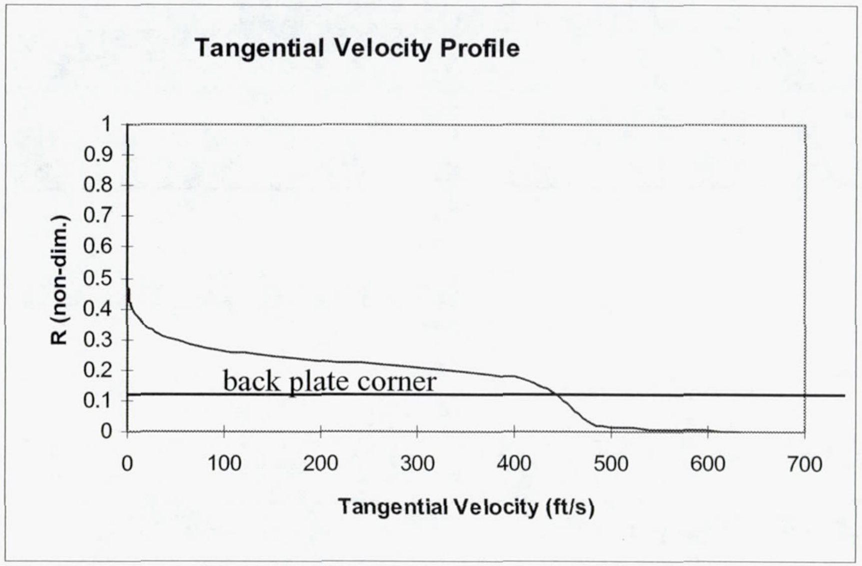
CFD Analysis Is Used As a Design Tool

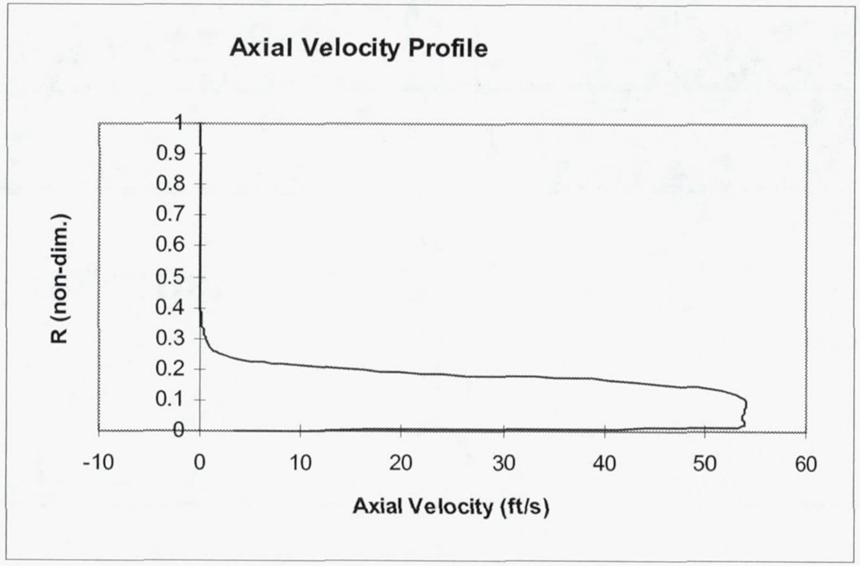


Current Brush seal w/Line-to-line in S-S Conditions
Velocity profiles from the Rotor surface towards bristle pinch point

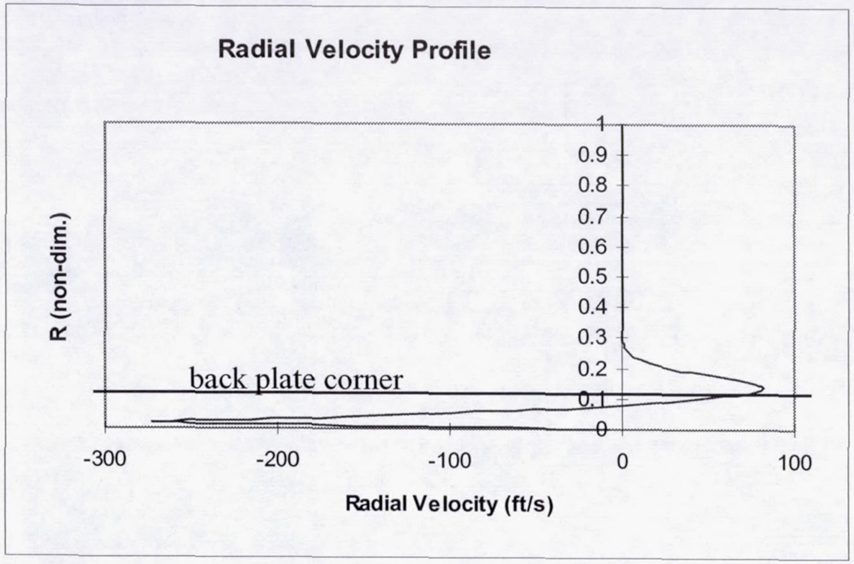


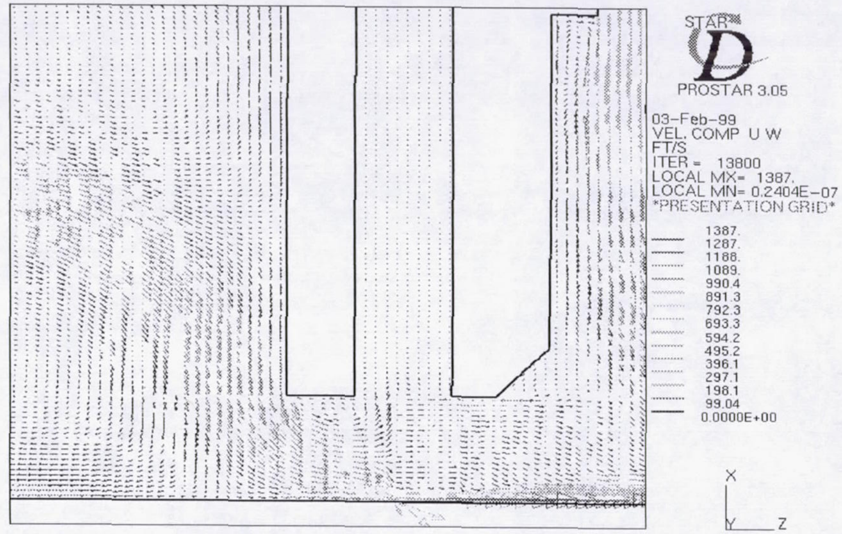


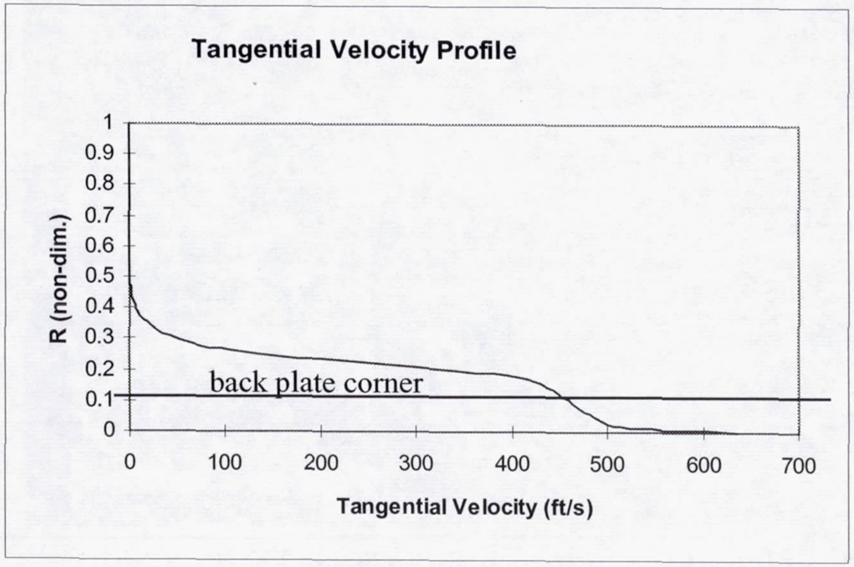


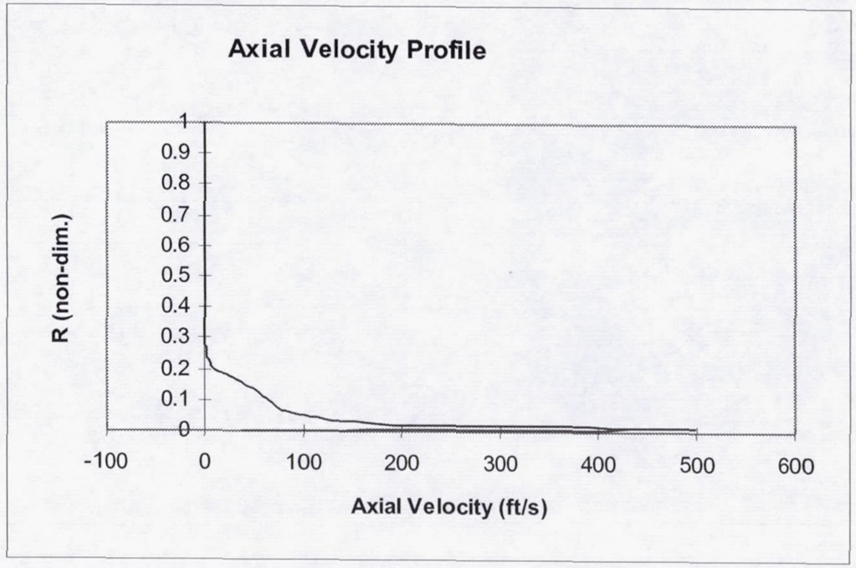


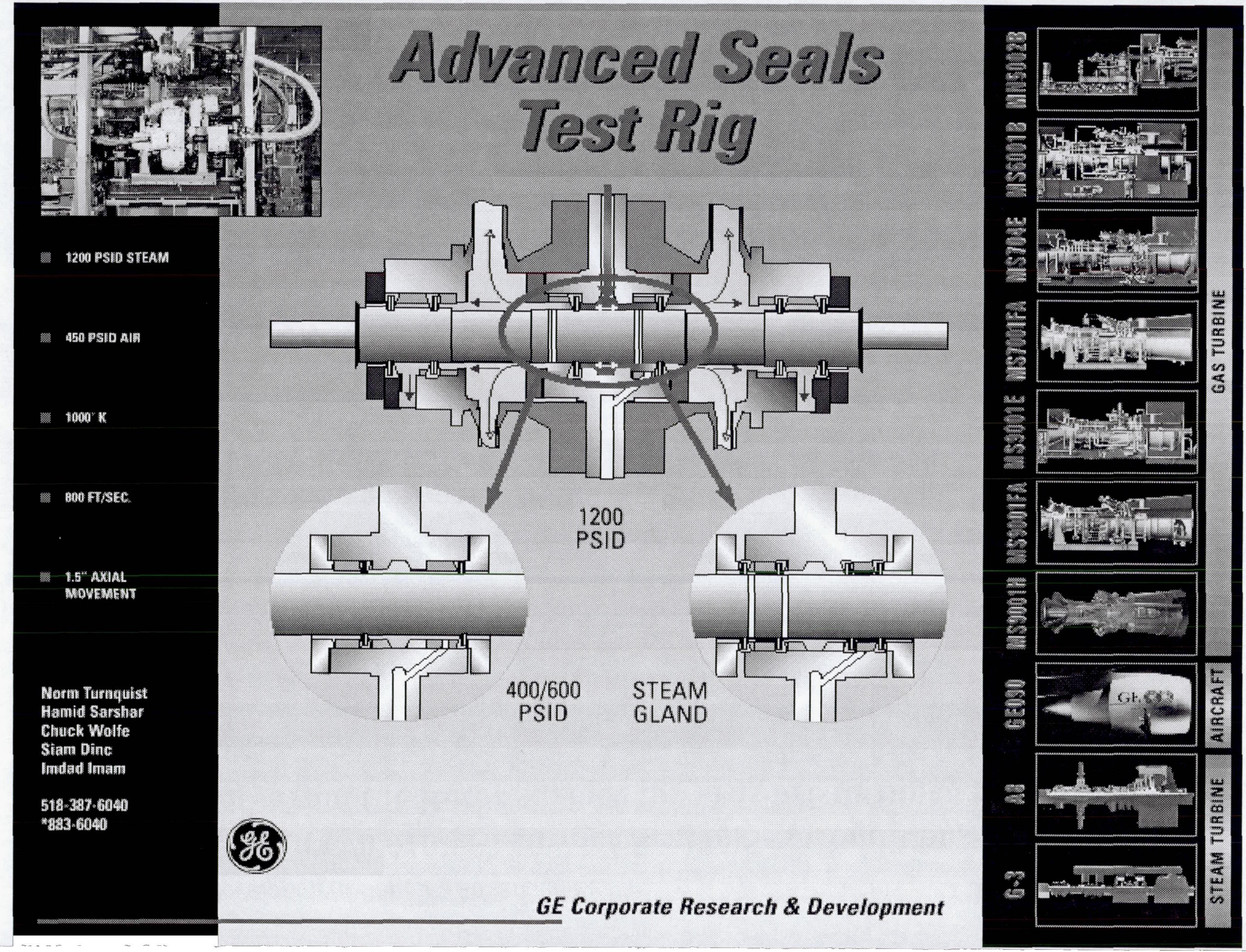
Current Brush seal w/0.010” Clearance Seal in S-S Conditions
Velocity profiles from the Rotor surface towards bristle pinch point











Advanced Seals
Test Rig
1200 PSID STEAM
450 PSID AIR
1000° K
800 FT/SEC.
1.5" AXIAL MOVEMENT
Norm Turnquist
Hamid Sarshar
Chuck Wolfe
Siam Dinc
Imdad Imam
518-387-6040
*883-6040
1200 PSID
400/600 PSID
STEAM GLAND
GE90
GAS TURBINE
AIRCRAFT
STEAM TURBINE
GE Corporate Research & Development

Technology Status/Milestones:

- **Transient Capability/Stable Brush Seals**
  - From current seals to 3-5 times dynamically more aggressive engine seals
- **High Surface Speed**
  - From 400 f/s of AE seals to 800 f/s of GT seals
  - From 800 f/s to 1600 f/s surface speed
- **High Pressure Loading**
  - From 100 psi two stg seals to 400 psi single stage seal design
  - Moving to high delp multi-stage seal designs
- **High Swirl Flow Field**
  - Swirl ratios of current applications are 0.3 moving to 0.6 - 0.9 region
- **Air Temperature**
  - From 700 F to 1200 - 1800F temperatures
- **Seal Life and Durability**
  - GT fleet leader w/35,000 field hrs w/minimum degradation
  - ST fleet leader 15,000 hrs w/minimum degradation
- **Rotor Surface**
  - Ceramic coated AE rotors to uncoated GT and ST applications
  - Interrupted surface at ST bucket tip seals
- **Rotor Dynamics/Rub Tolerant Soft Seal Design**
  - Moving towards “Rub Tolerant Soft Seals”

36 Publications, Patents Activity: 65 Total; 15 issued, 20 Pending, 30 Additional New Dockets

GE INDUSTRIAL TURBINE ADVANCED SEAL DEVELOPMENT

Ray Chupp, Saim Dinc, and Norm Turnquist
General Electric Corporate Research and Development
Niskayuna, New York

Research & Development Center - Advanced Seals

GE Industrial Turbine Advanced Seal Development

Objective:

Advanced Seals Development
Applications

Overview:

Sealing Areas Being Developed
Types of Sealing
System Level Analyses/Adjustments
Applications
Field Validation
Summary

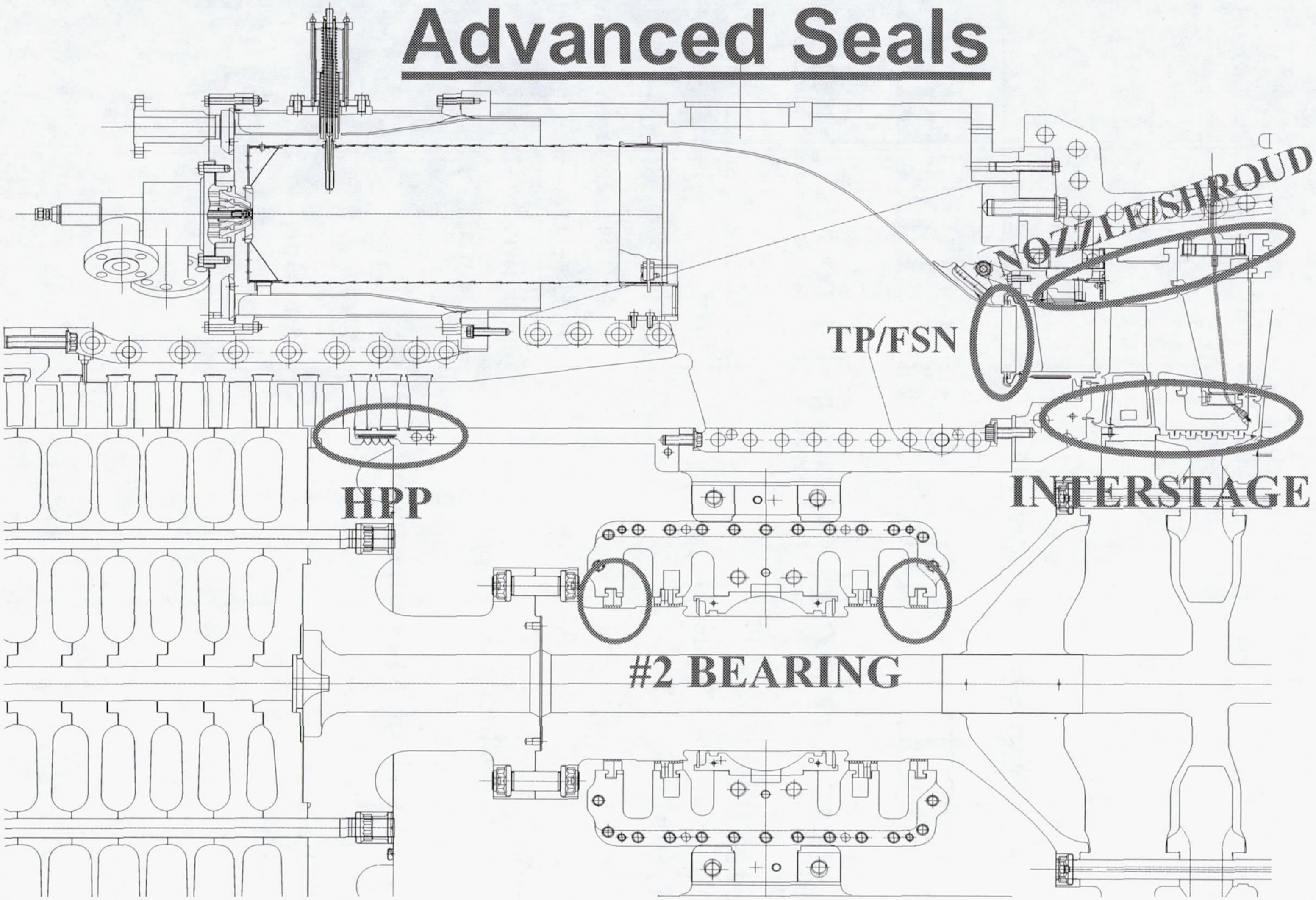
GE Participating Groups:

- **CRD**
- **GE Power Systems--**
  Gas Turbines--new products and services
- **GE Power Systems--**
  Steam Turbines

Presenters:

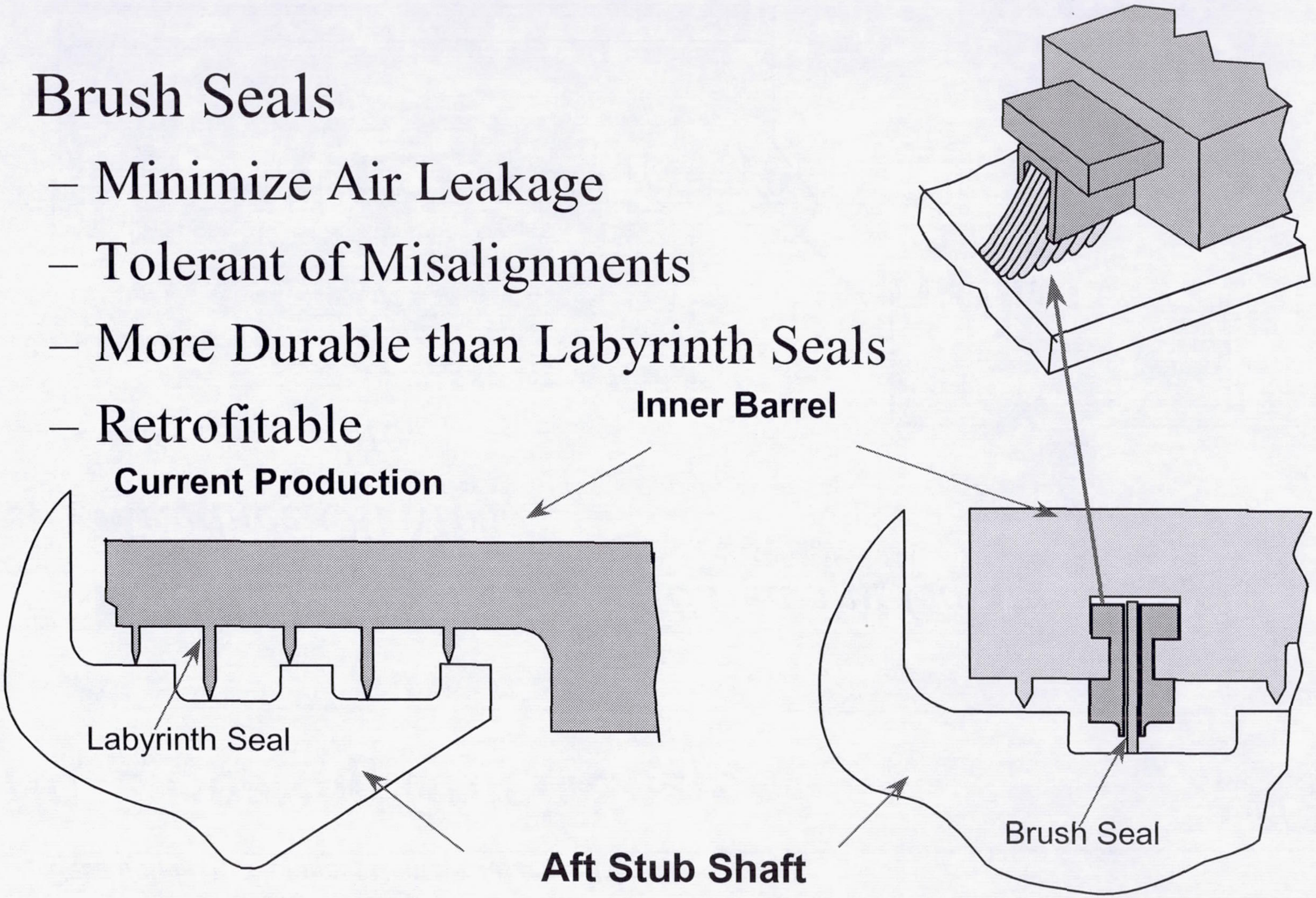
- **Ray Chupp**
- **Saim Dinc**
- **Norm Turnquist**

Advanced Seals



High-Pressure Packing / Inner Barrel

- Brush Seals
  - Minimize Air Leakage
  - Tolerant of Misalignments
  - More Durable than Labyrinth Seals
  - Retrofitable



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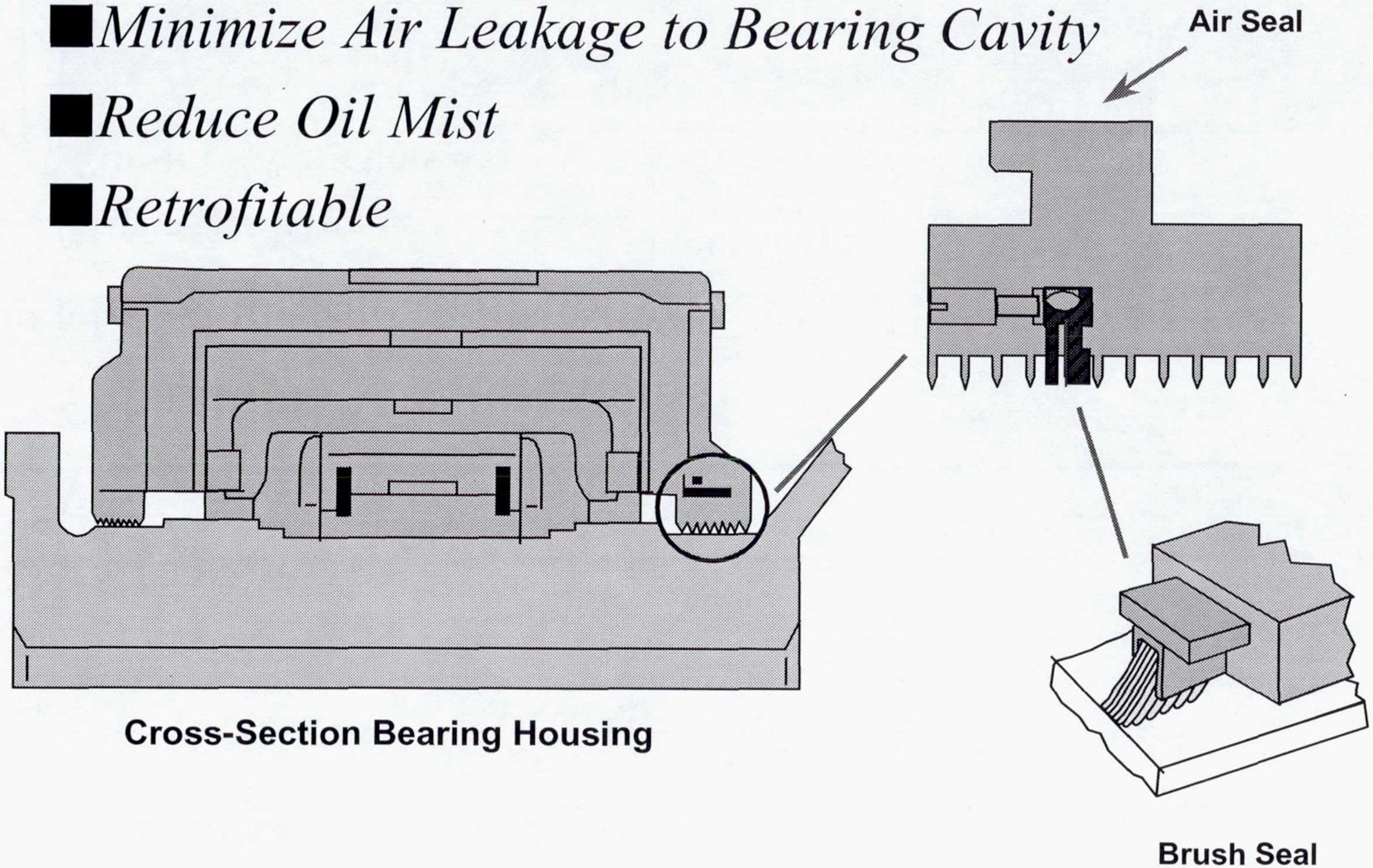
No. 2 Bearing Brush Seals

- *Minimize Air Leakage to Bearing Cavity*
- *Reduce Oil Mist*
- *Retrofitable*



Cross-Section Bearing Housing

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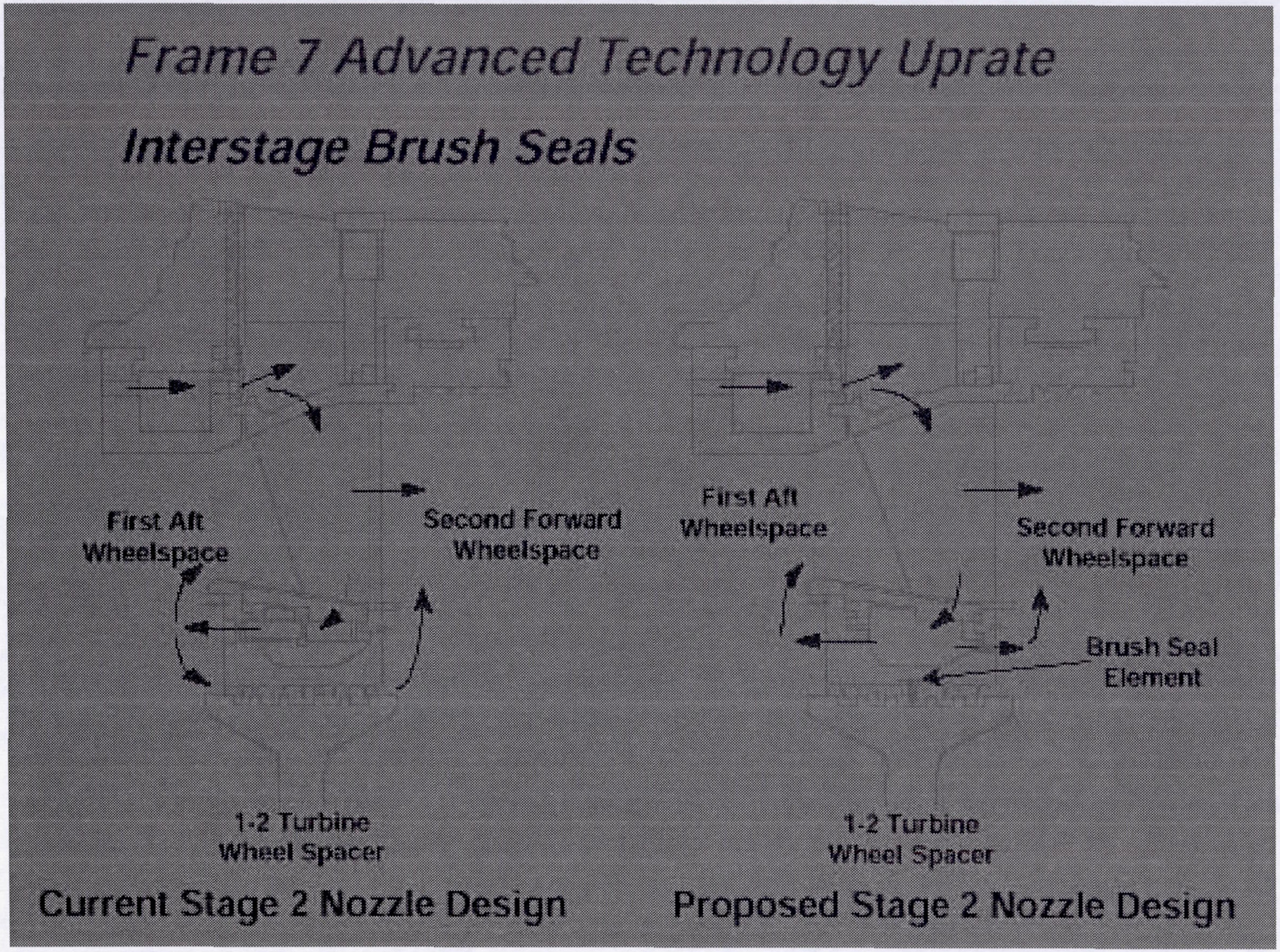
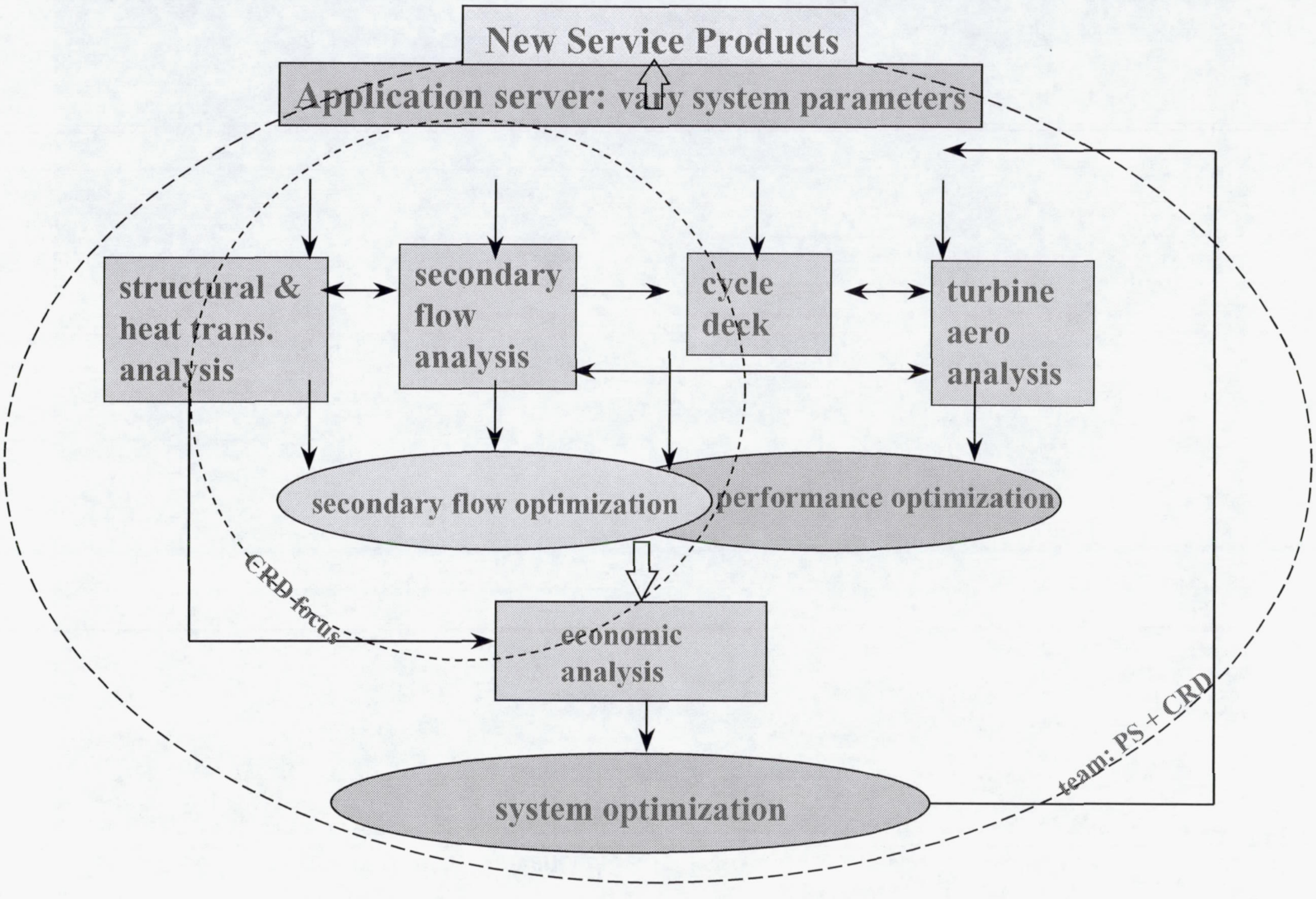
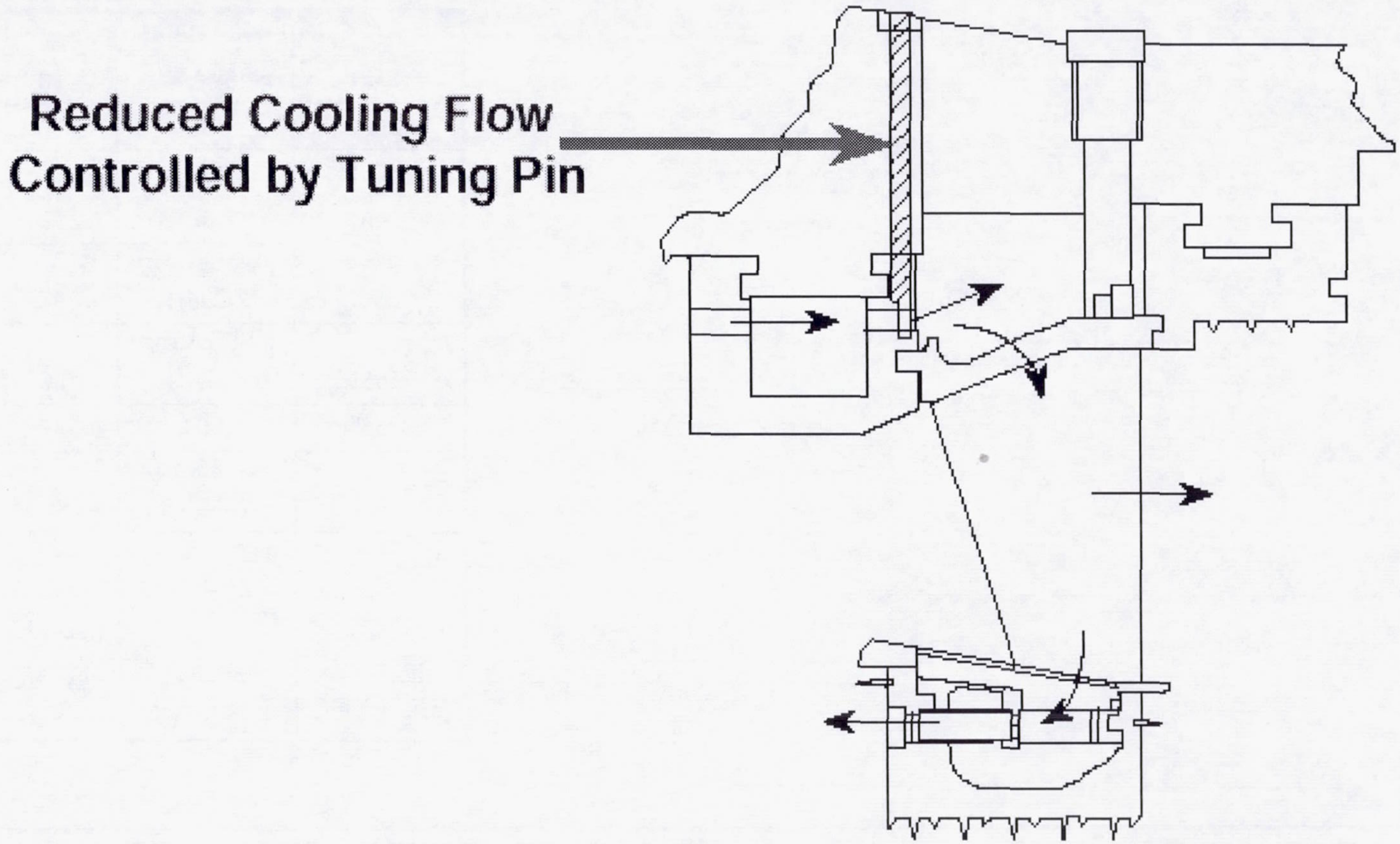


Gas Turbine System Level Secondary Flow/Performance Analysis



Air System Adjustments to Achieve Reduced Leakage with Sealing Changes



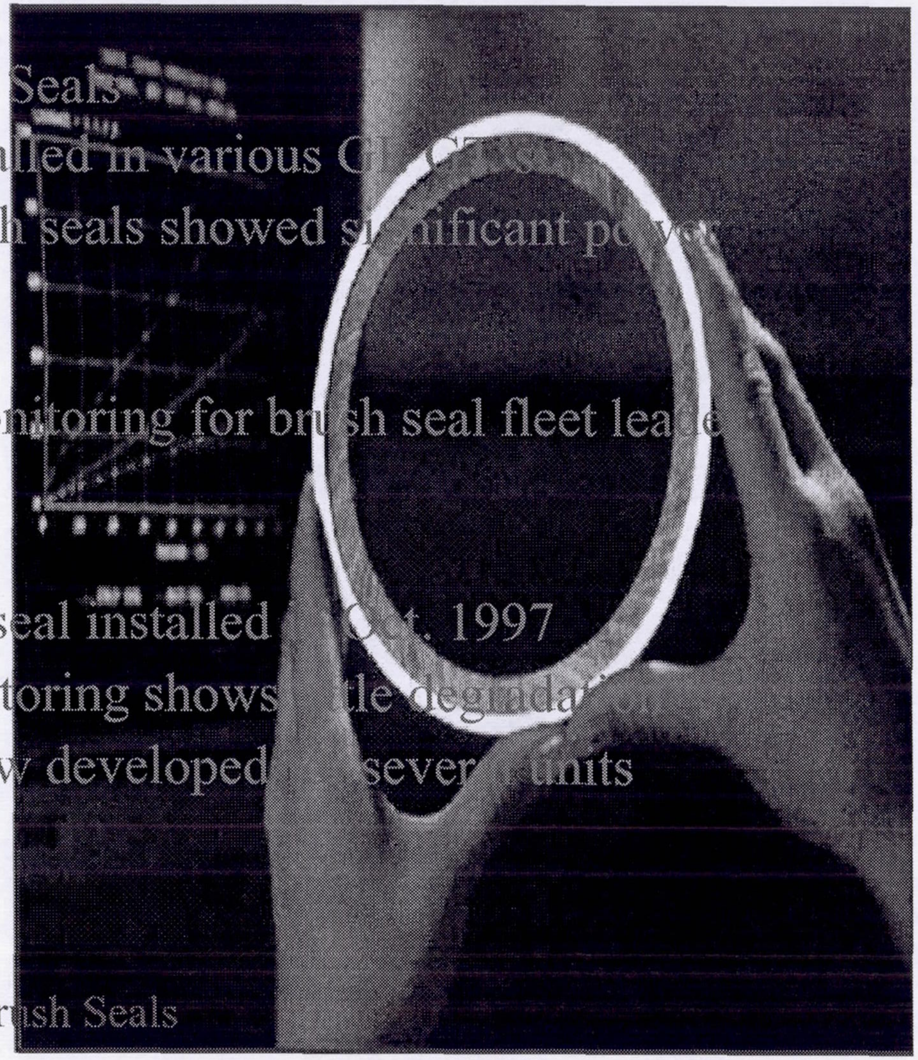
Frame Size	Output (MW) (approx)	Brush Seal Location	Commercial -ization Date
9E	123	HPP,#2 Bearing Seal	1996
7EA	85	HPP,#2 Bearing Seal	1996
6B	38	HPP	1996
52D	32	HPP,#2 Bearing Seal	1997
52C	28	HPP,#2 Bearing Seal	1997
51P	27	HPP	1997
32J	11	HPP	1997
32G	6	HPP	1997
7EA	**85**	**Interstage Diaphragm**	**1998**

CM&U Performance Enhancement Update 1999 GTUA

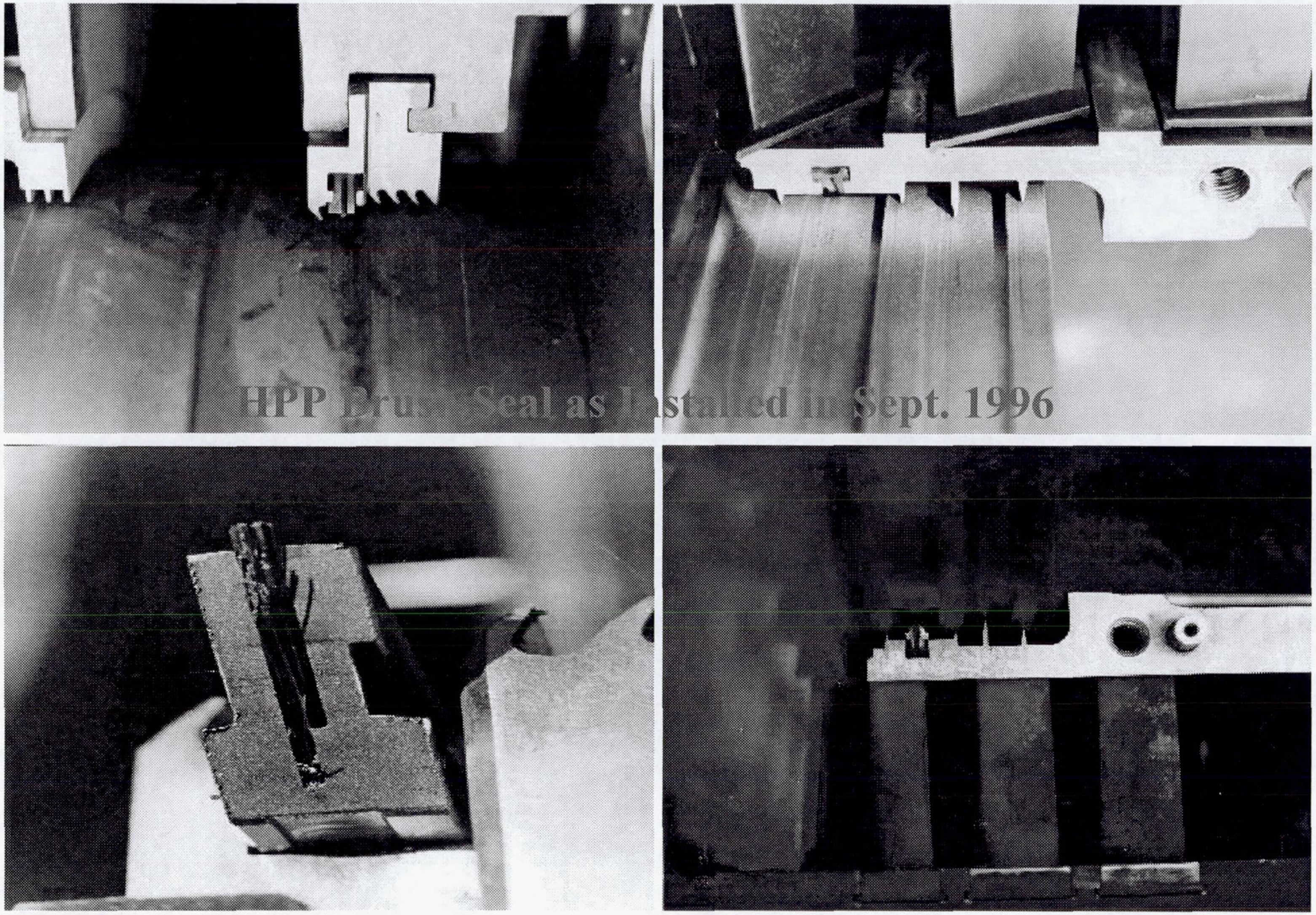
	3/2H & J	5/1N & P	5/2 B & C	6/1B	7/1 B&E	9/1 B & E
HPP Brush Seal	X	X	X	X	X	X
#2 Bearing Brush Seal	-	-	X	-	X	X
Stage 2&3 Honeycomb Shroud Seals	X	X	X	X	X	X
Stage 1 Shroud Seals	X	X	X	X	X	X
Inner Stage Brush Seal	-	X	-	X	X	X

Brush Seal Activities

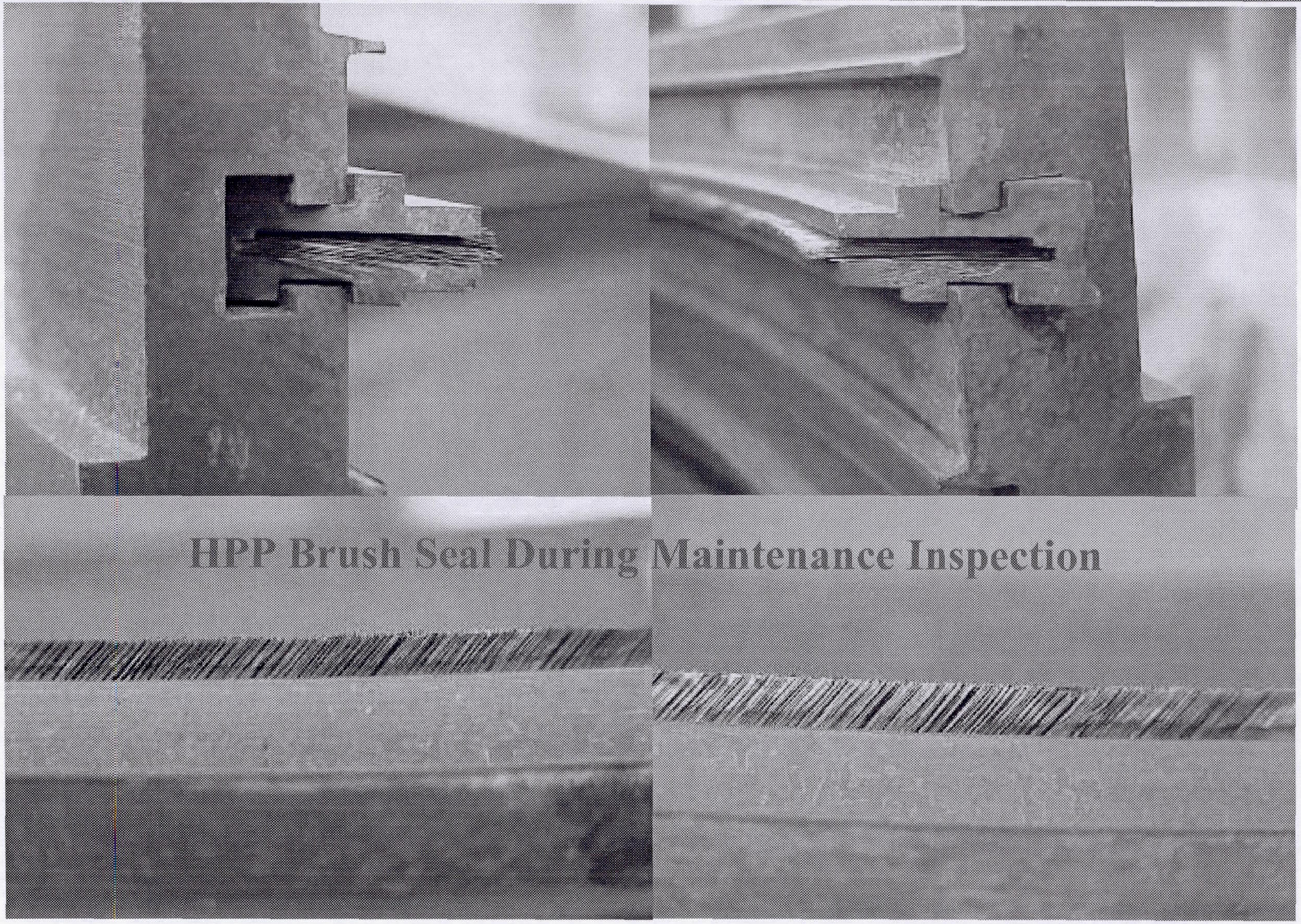
- Gas Turbine
  - –HPP and #2 Bearing Brush Seals
    - 120+ brush seal sets installed in various GE GTs
    - HPP and #2 bearing brush seals showed significant power increase in August 1996 test
    - 4 years field data and monitoring for brush seal fleet leader 30,000 hours
  - –Interstage Brush Seal
    - Prototype 2nd stg brush seal installed in Oct. 1997
    - 10 Months of close monitoring shows little degradation
    - Interstage brush seals now developed for several units
- Steam Turbine
  - – Interstage Packing Brush Seals
  - – Shaft End packings
  - – HP and IP Section Bucket Tip Brush Seals



Research & Development Center - Advanced Seals

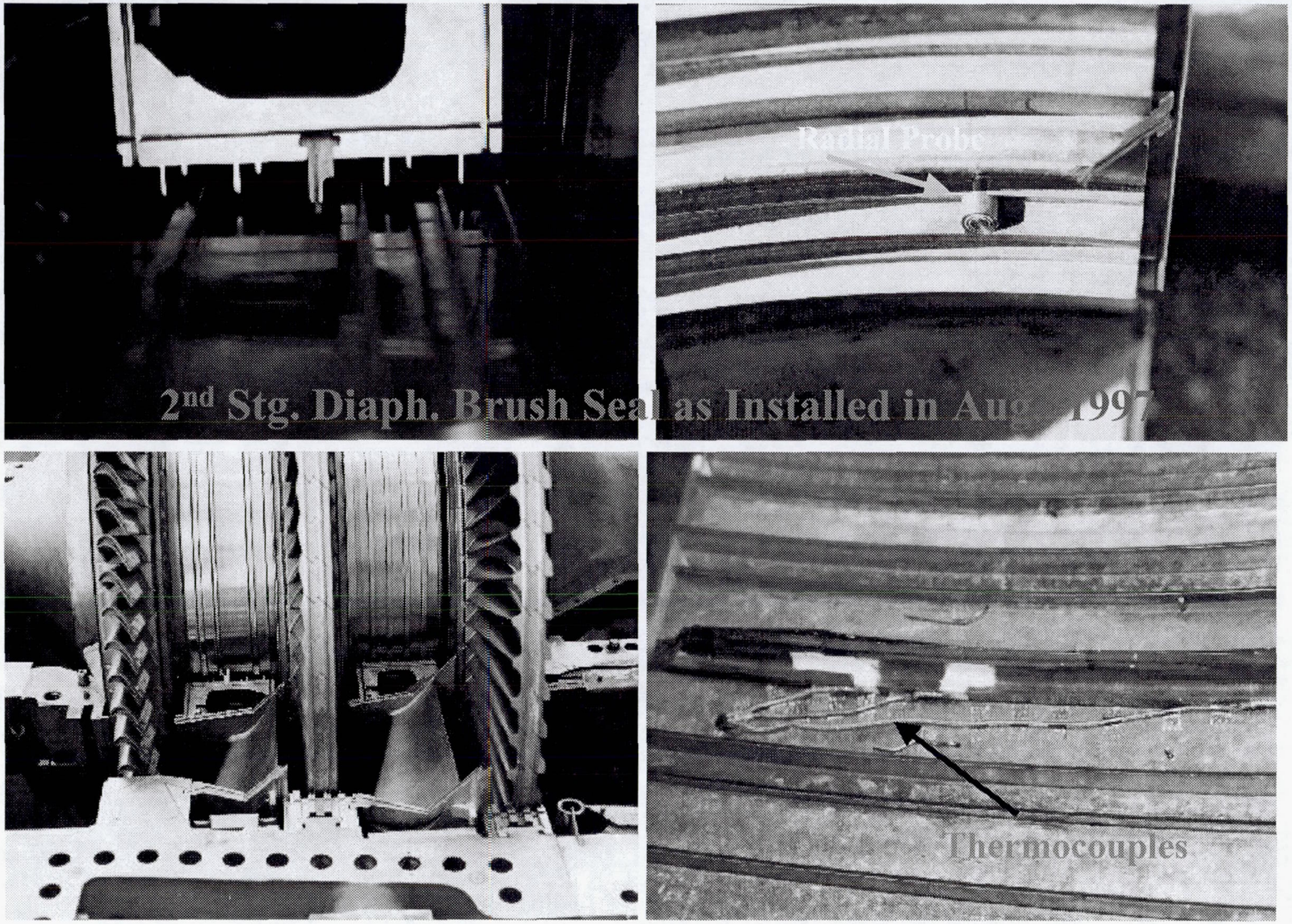


HPP Brush Seal as Installed in Sept. 1996



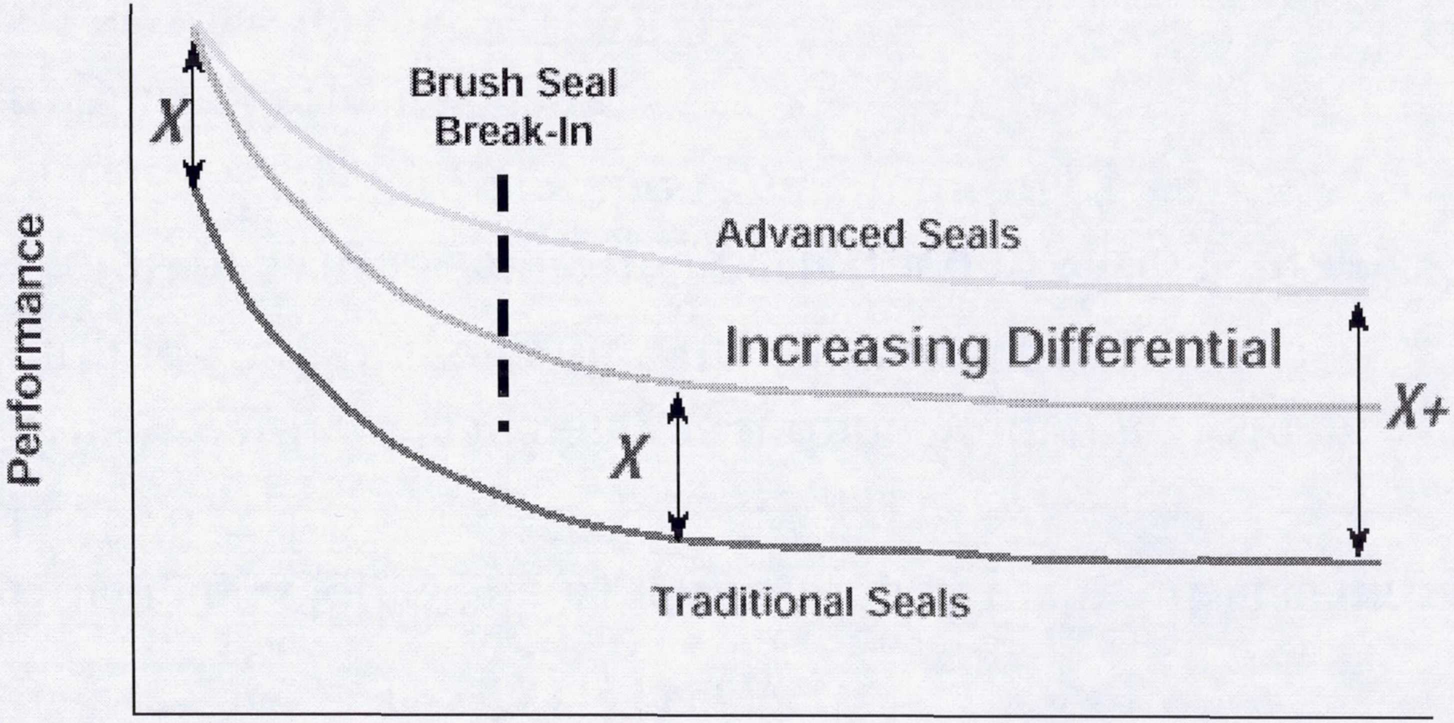
HPP Brush Seal During Maintenance Inspection

Research & Development Center - Advanced Seals



Gas Turbine Advanced Seals

- Rub Tolerant Rotating Seals Provide Sustained Performance Gains That Increase Over Time



Summary

- Brush and cloth seals were installed in many GE gas turbines in 1998 & 1999
- Brush seal fleet leaders: gas turbine 35,000 hrs; steam turbine 15,000 hrs--both with minimum degradation
- Prototype brush seal testing performed in various Frame 3, 5, 6, 7 and 9 gas turbines and in steam turbines
- Exploring brush seals for:
  - New gas turbines-- F, FB, H
  - Operating & new steam turbines
  - Generators & compressors
- Cloth seals:
  - In operation in E machines (in leader unit for ~3 years)
  - In production in some F machines (in leader unit for ~2 years)
  - Being introduced in other F machines and H machines

PRESSURE BALANCED, LOW HYSTERESIS FINGER SEAL TEST RESULTS

Gul K. Arora
AlliedSignal Engines
Phoenix, Arizona

Margaret Proctor and Bruce M. Steinetz
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio

Irebert R. Delgado
U.S. Army Research Laboratory
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio

Pressure Balanced, Low Hysteresis Finger Seal Test Results

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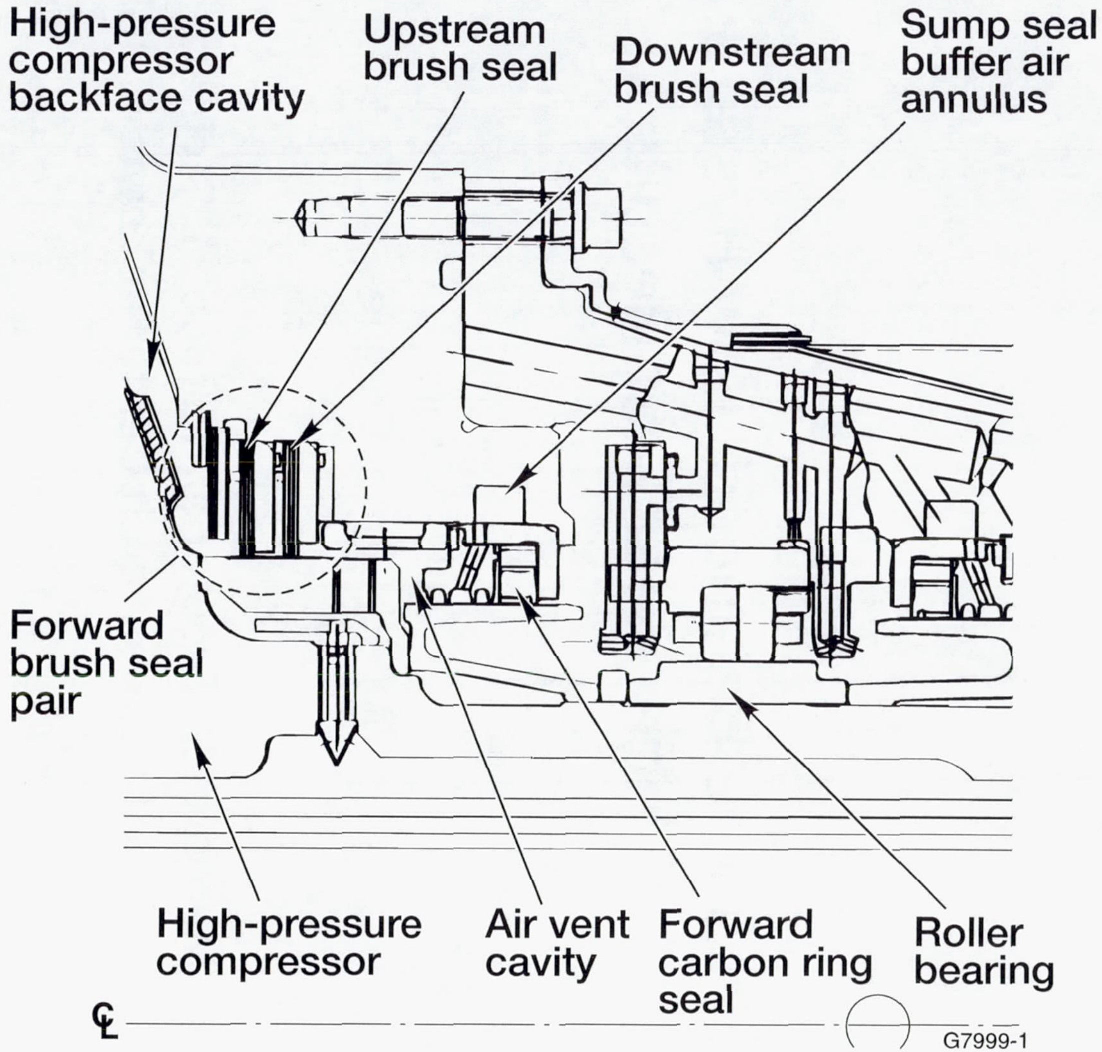
Allied Signal Engines

Margaret P. Proctor and Bruce M. Steinetz
NASA Glenn Research Center at Lewis Field

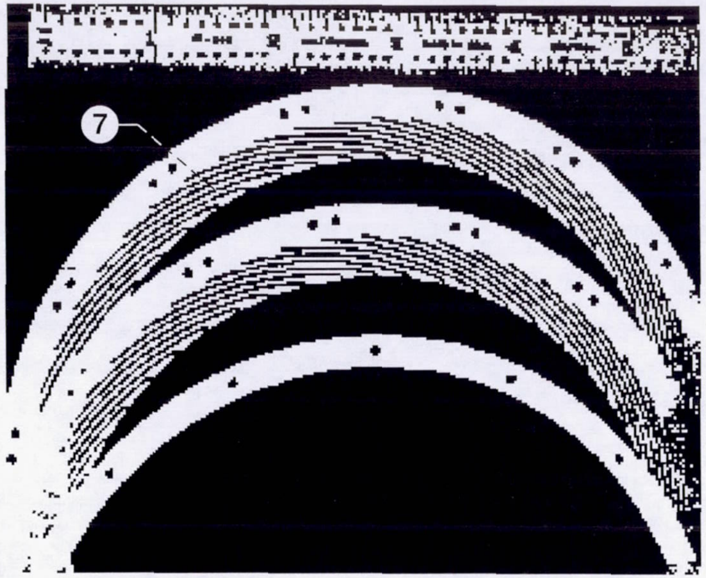
Irebert R. Delgado
Army Research Laboratory
NASA Glenn Research Center at Lewis Field

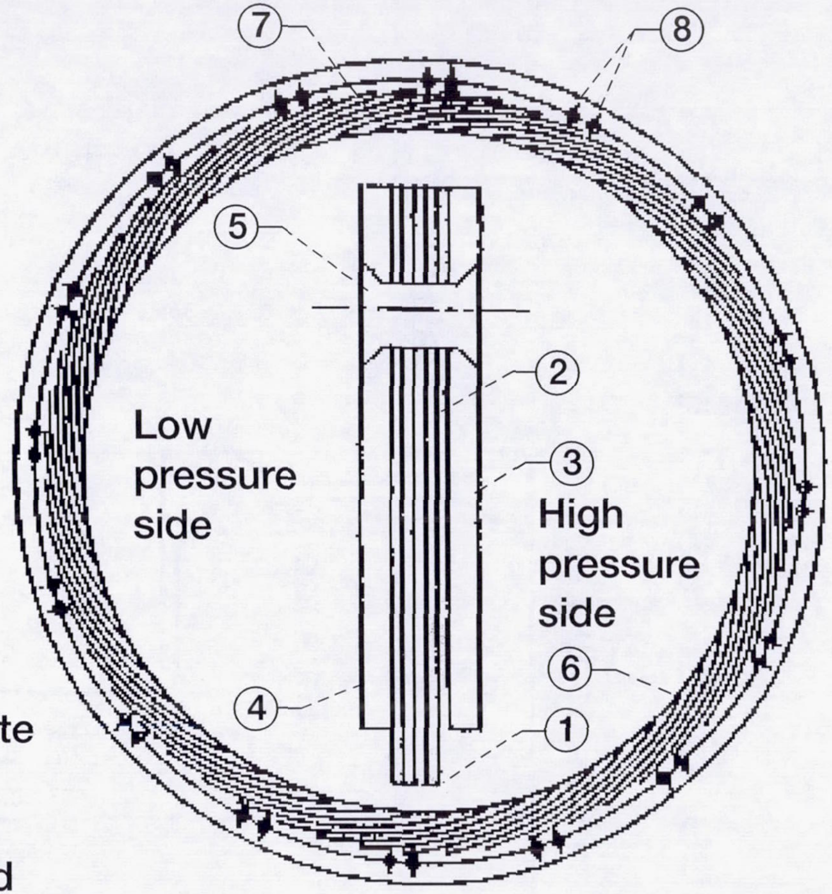
Typical Brush Seal Arrangement



CD-99-79381

Baseline Finger Seal and Its Nomenclature

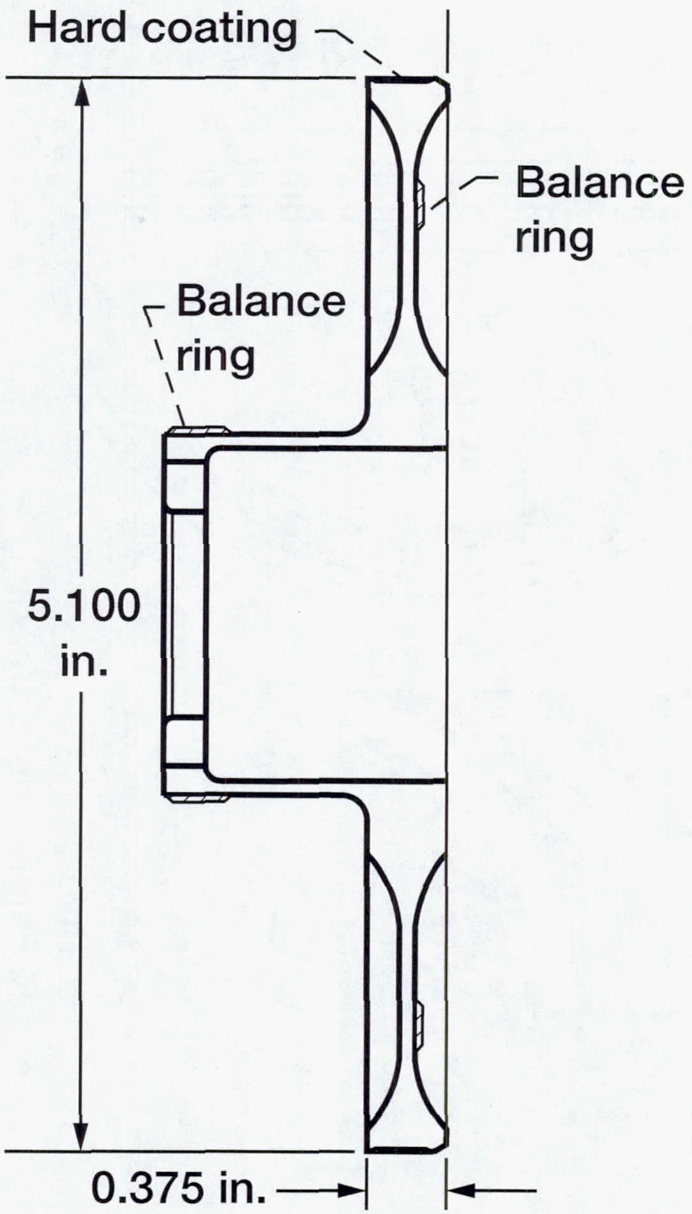




1. Finger element
2. Spacer
3. Forward cover plate
4. Aft cover plate
5. Rivet
6. Finger contact pad
7. Finger
8. Indexing and rivet holes

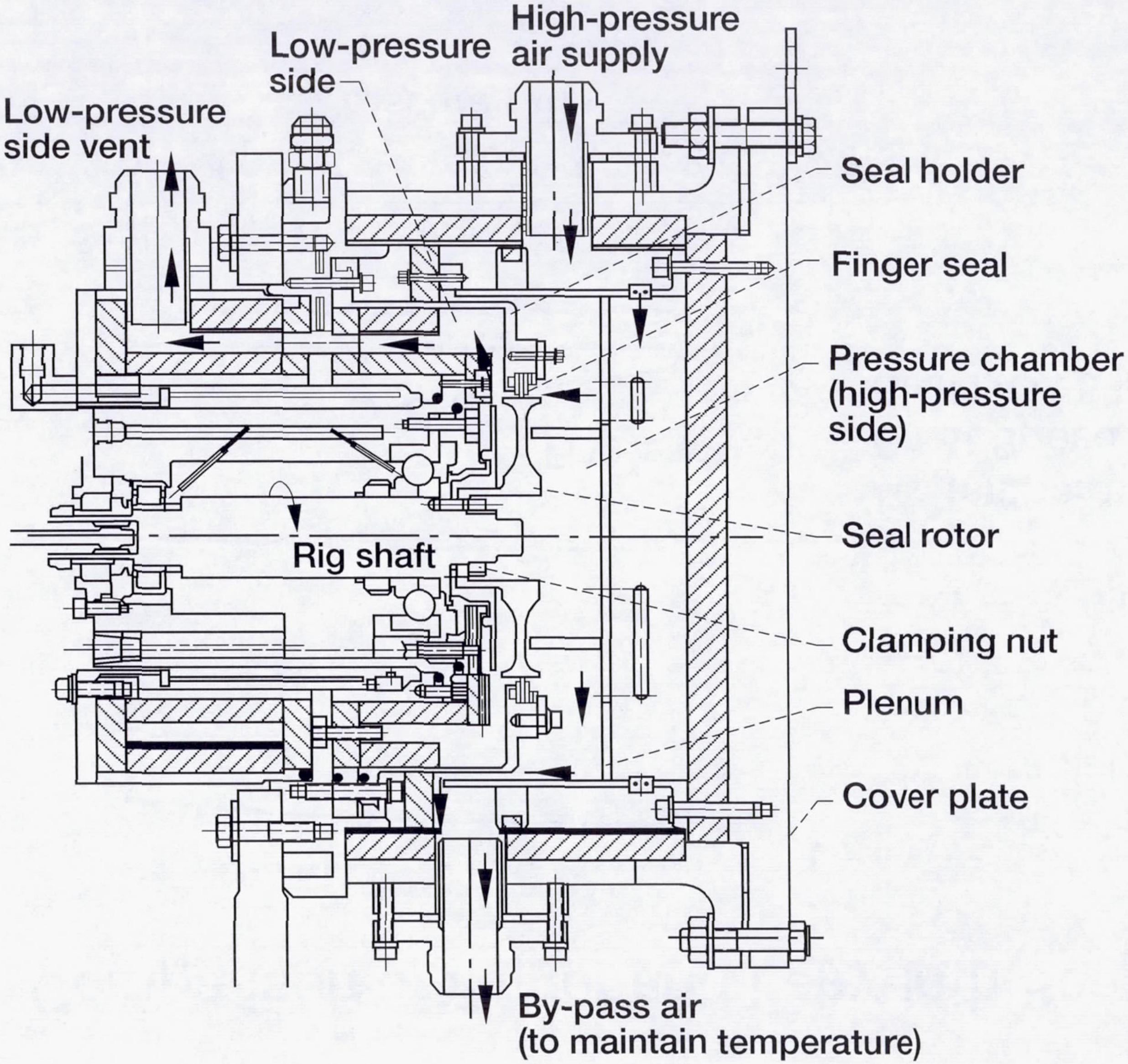
CD-99-79382

Finger Seal Test Rotor



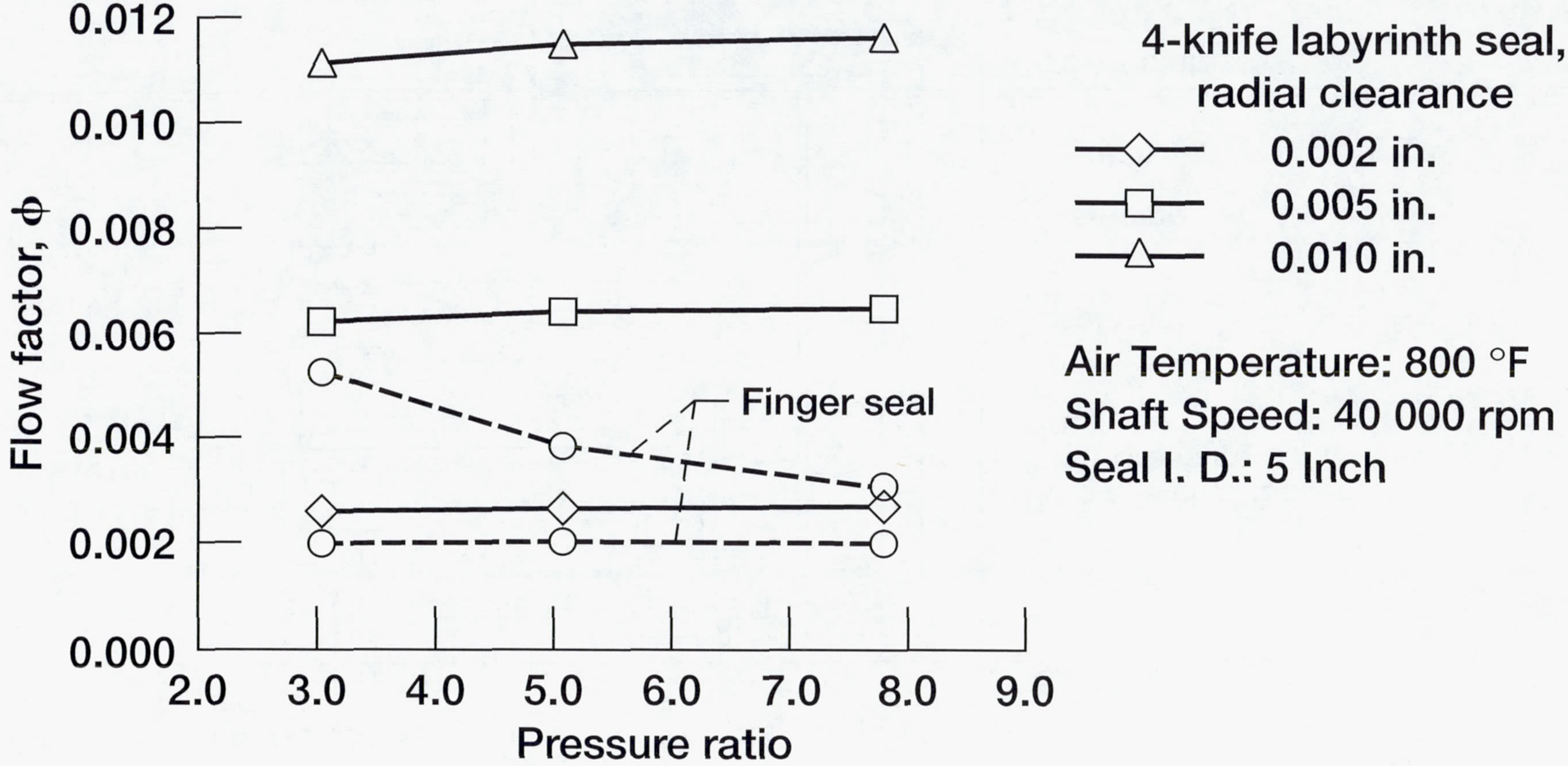
CD-99-79383

NASA Glenn Seal Rig Cross Section



CD-99-79384

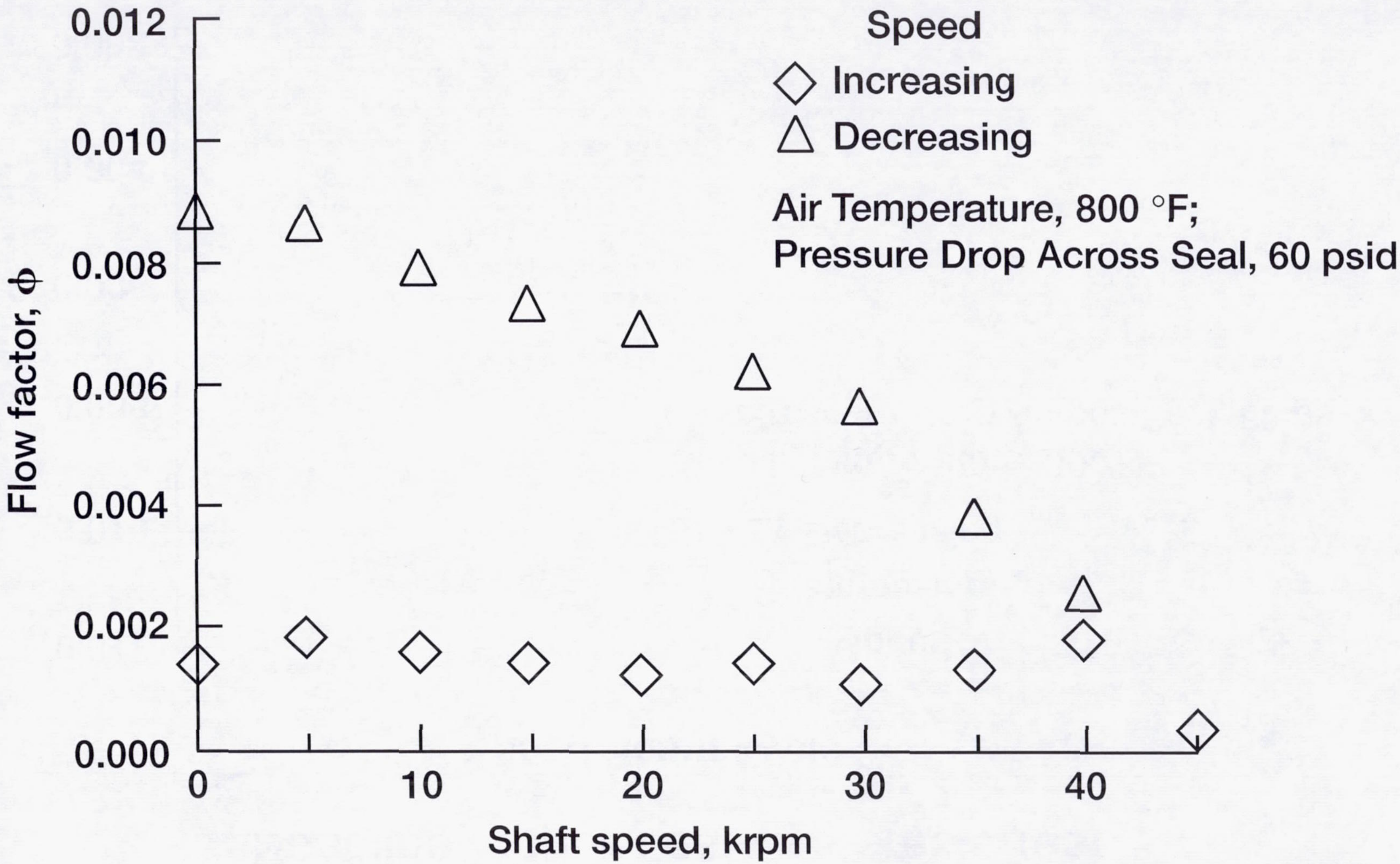
Comparison of Finger and Labyrinth Seal



CD-99-79385

Baseline Finger Seal Hysteresis Test

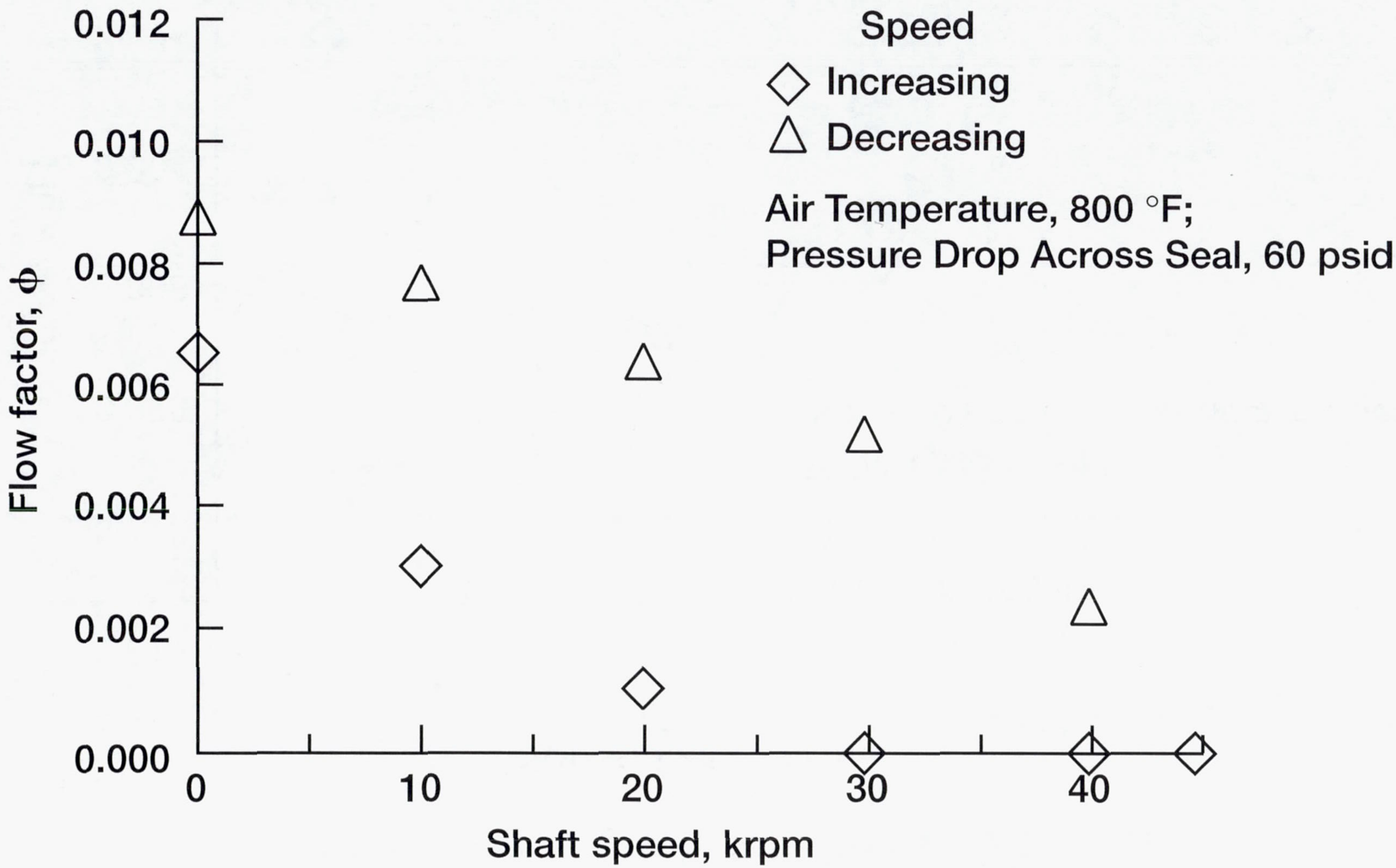
Speed Ramp Cycle 1



CD-99-79386a

Baseline Finger Seal Hysteresis Test

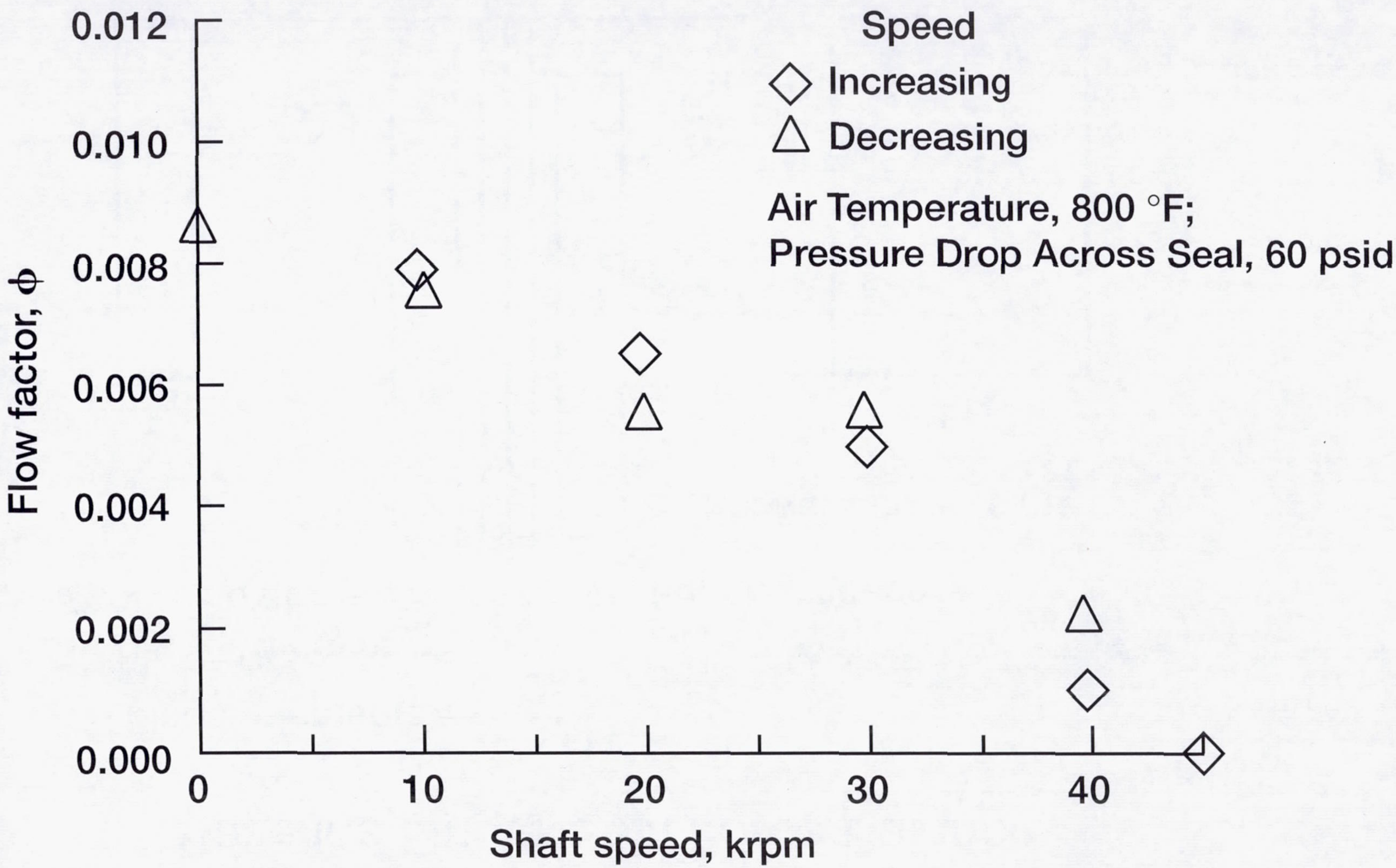
Speed Ramp Cycle 2



CD-99-79386b

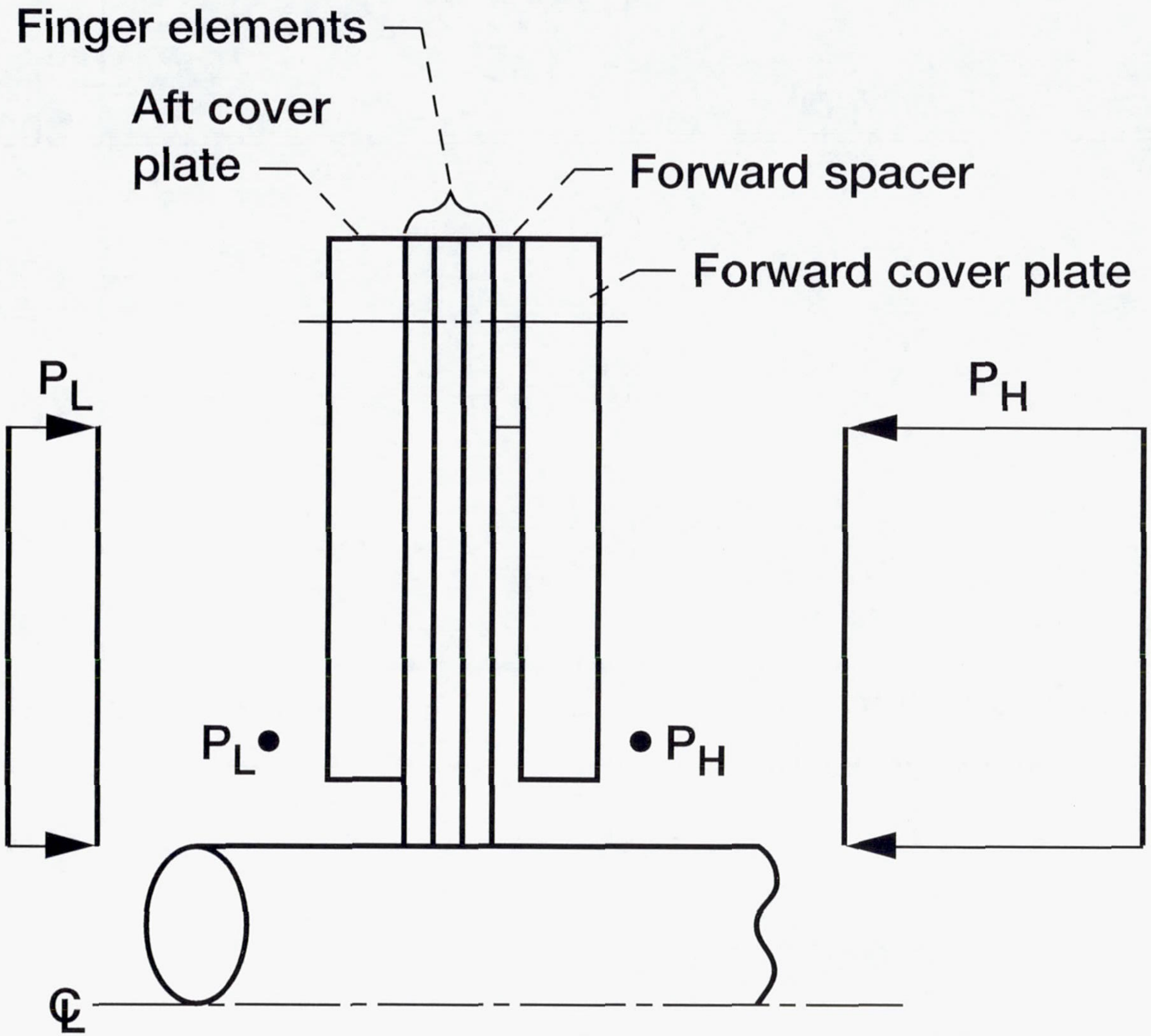
Baseline Finger Seal Hysteresis Test

Speed Ramp Cycle 3



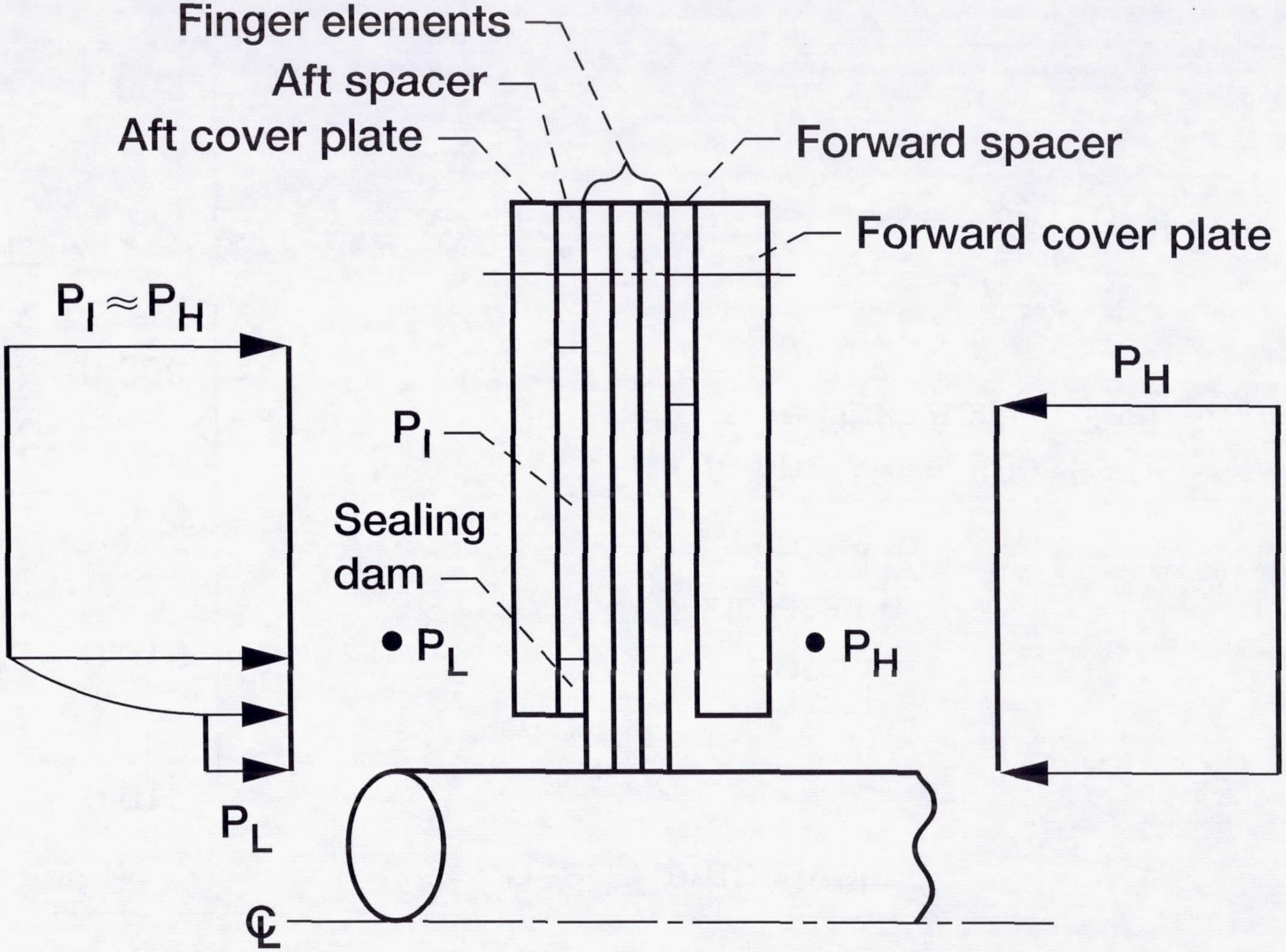
CD-99-79386c

Baseline Finger Seal Force Balance

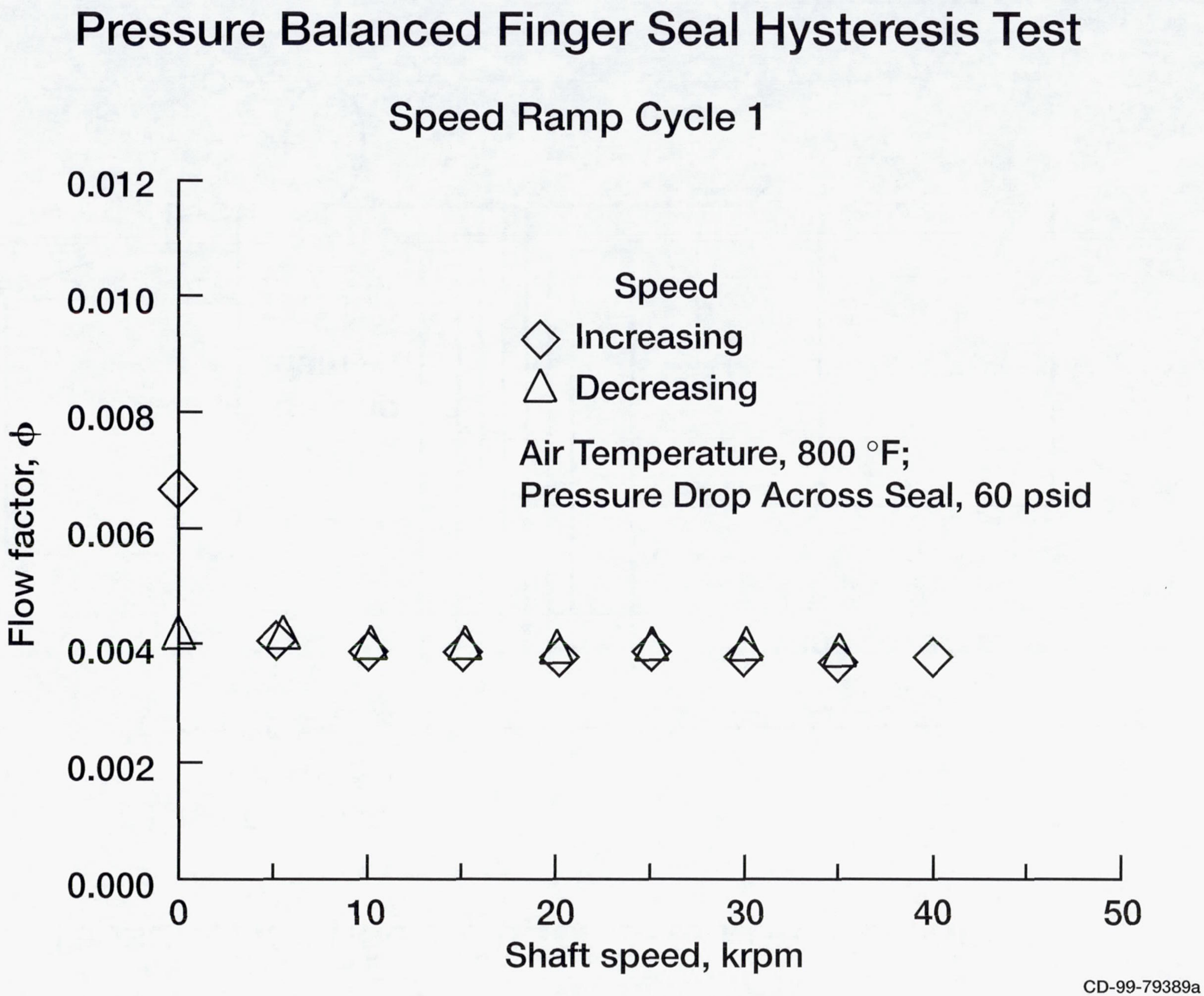


CD-99-79387

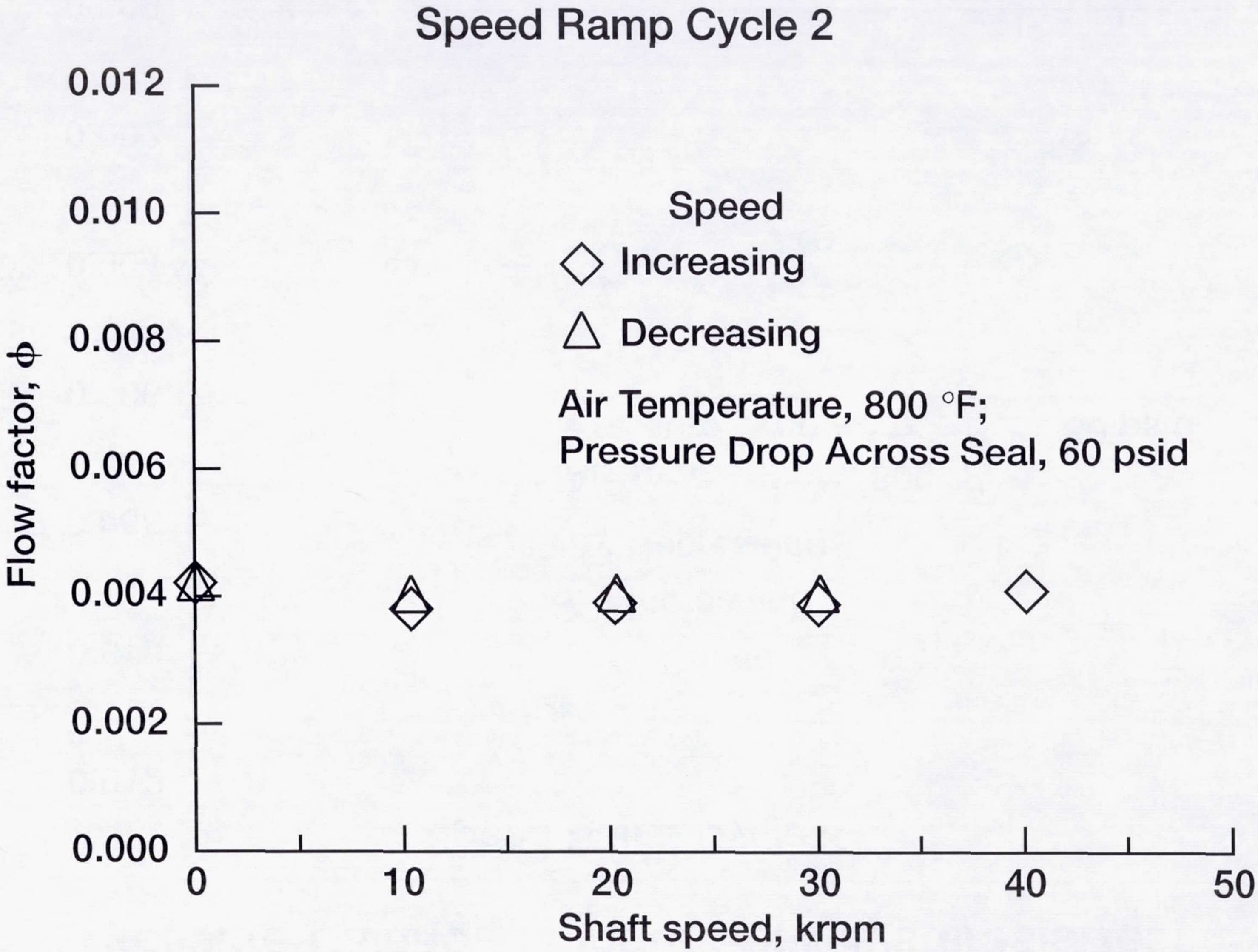
Pressure Balanced Finger Seal Force Balance



CD-99-79388


Pressure Balanced Finger Seal Hysteresis Test
Speed Ramp Cycle 1
Speed
Increasing
Decreasing
Air Temperature, 800 °F;
Pressure Drop Across Seal, 60 psid
Flow factor, ϕ
0.012
0.010
0.008
0.006
0.004
0.002
0.000
0
10
20
30
40
50
Shaft speed, krpm
CD-99-79389a

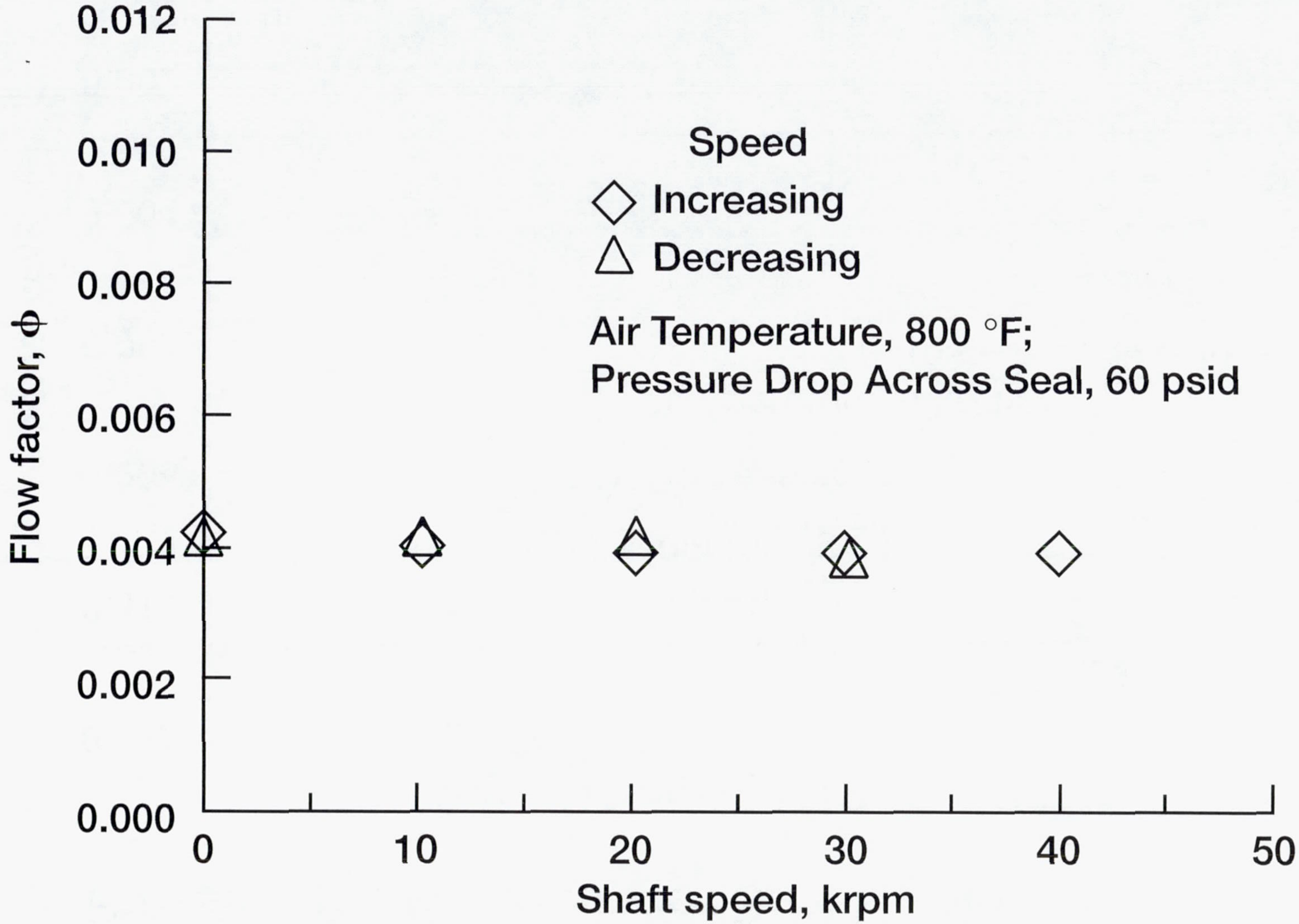
Pressure Balanced Finger Seal Hysteresis Test



CD-99-79389b

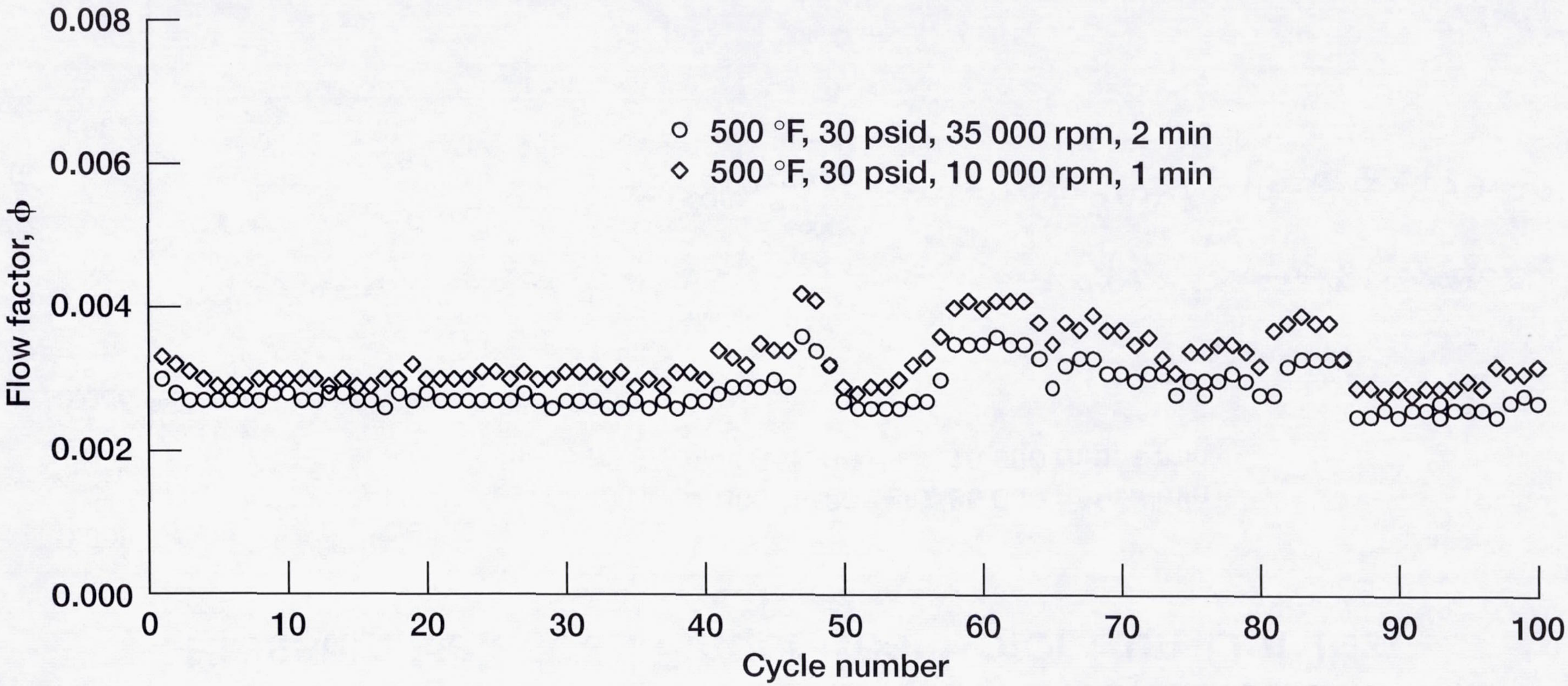
Pressure Balanced Finger Seal Hysteresis Test

Speed Ramp Cycle 3



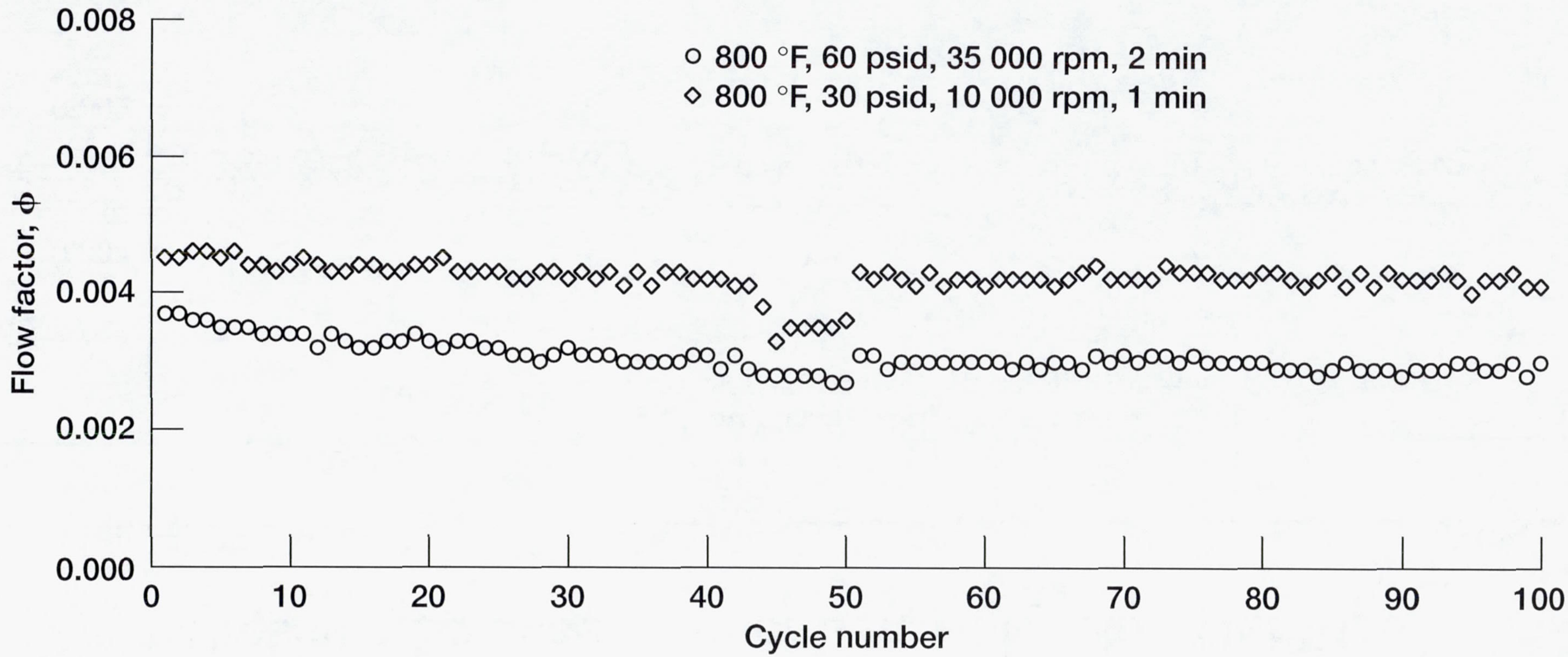
CD-99-79389c

Segment 1
Pressure Balanced Finger Seal Rotor Run-Out Test



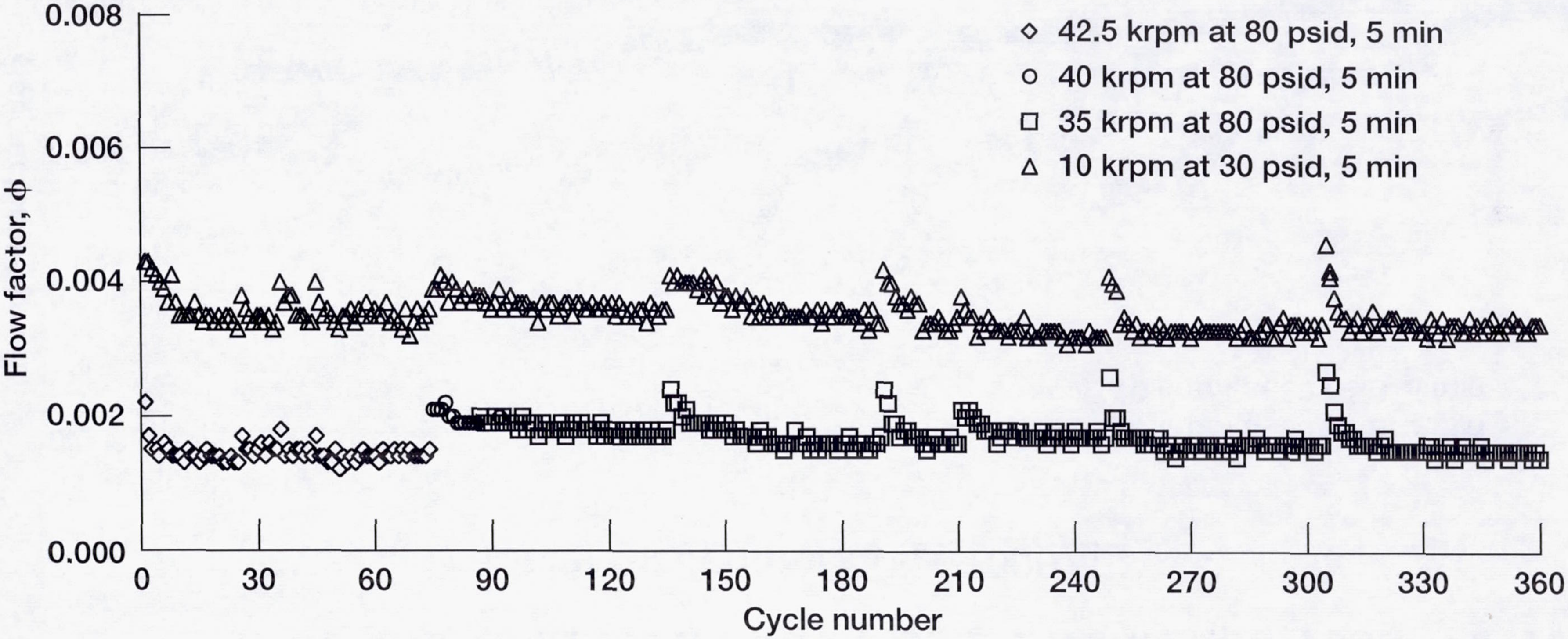
CD-99-79390

Segment 2
Pressure Balanced Finger Seal Rotor Run-Out Test



CD-99-79391

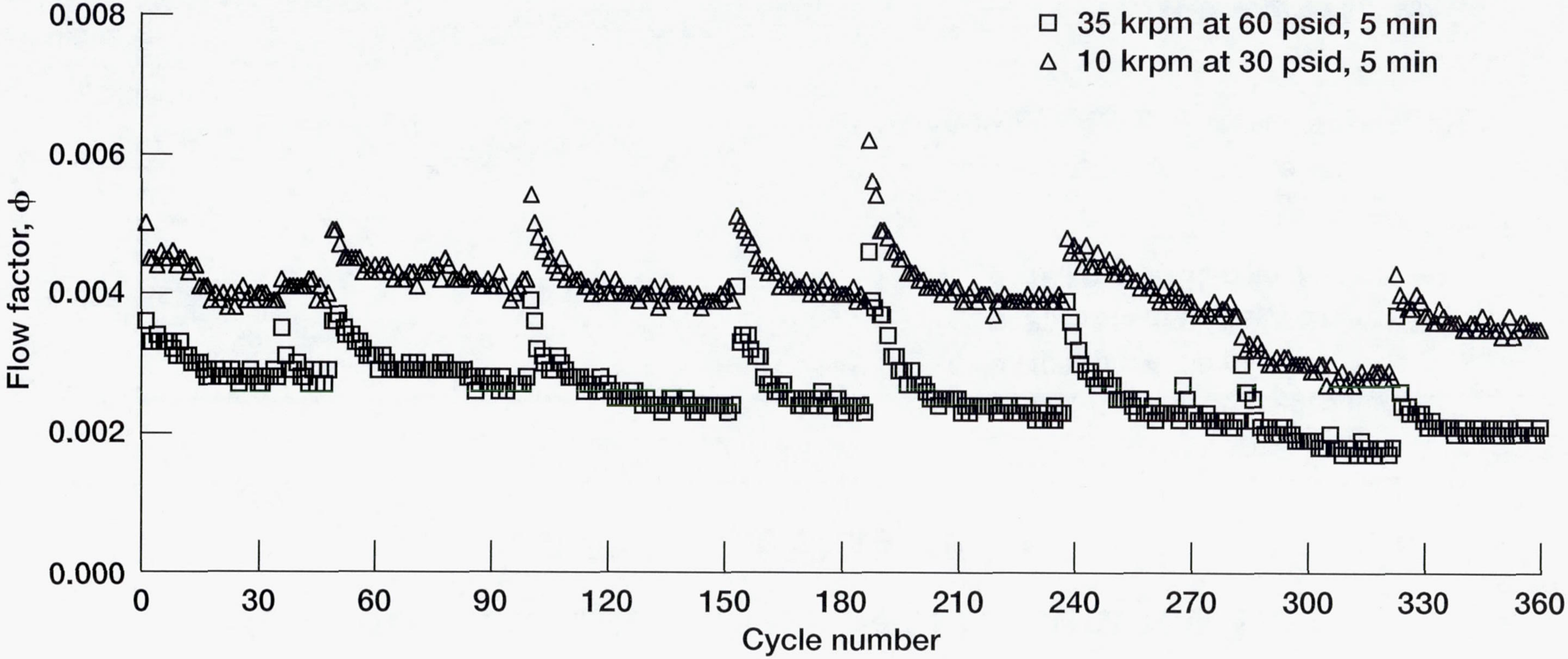
Segment 1
Pressure Balanced Finger Seal Endurance Test
Inlet Air Temperature, 800 °F



CD-99-79392

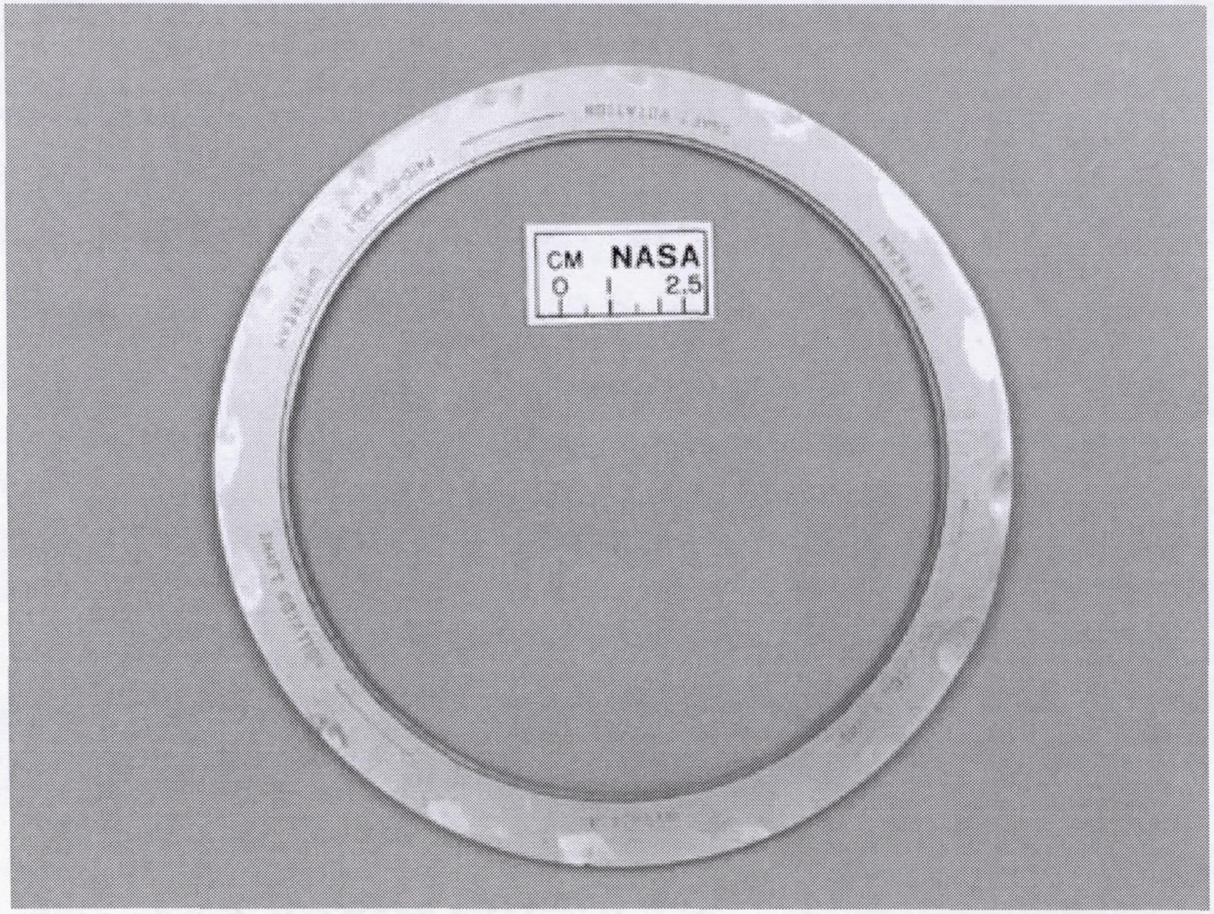
Segment 2
Pressure Balanced Finger Seal Endurance Test

Inlet Air Temperature, 1000 °F



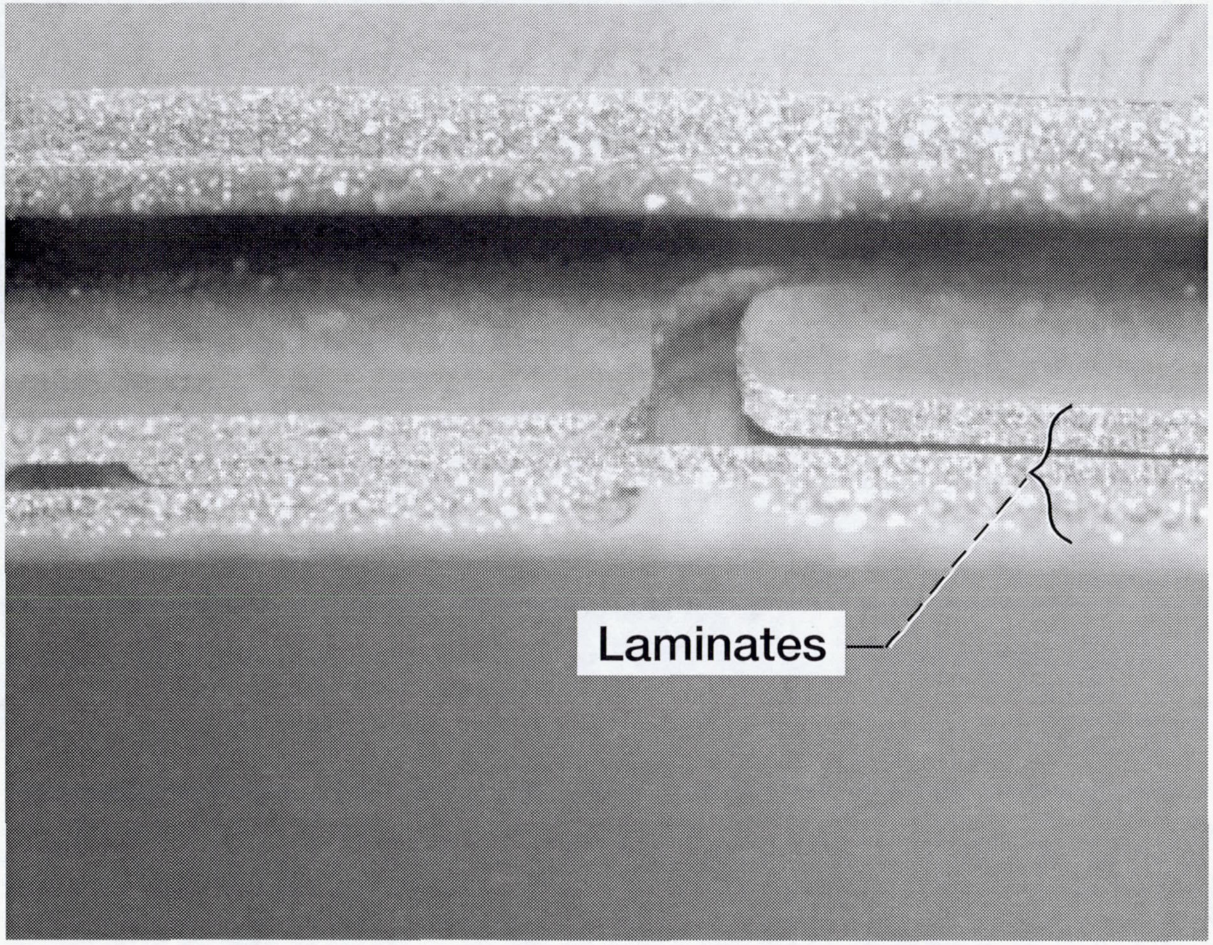
CD-99-79393

Overview of Pressure Balanced Finger Seal Prior to Endurance Test



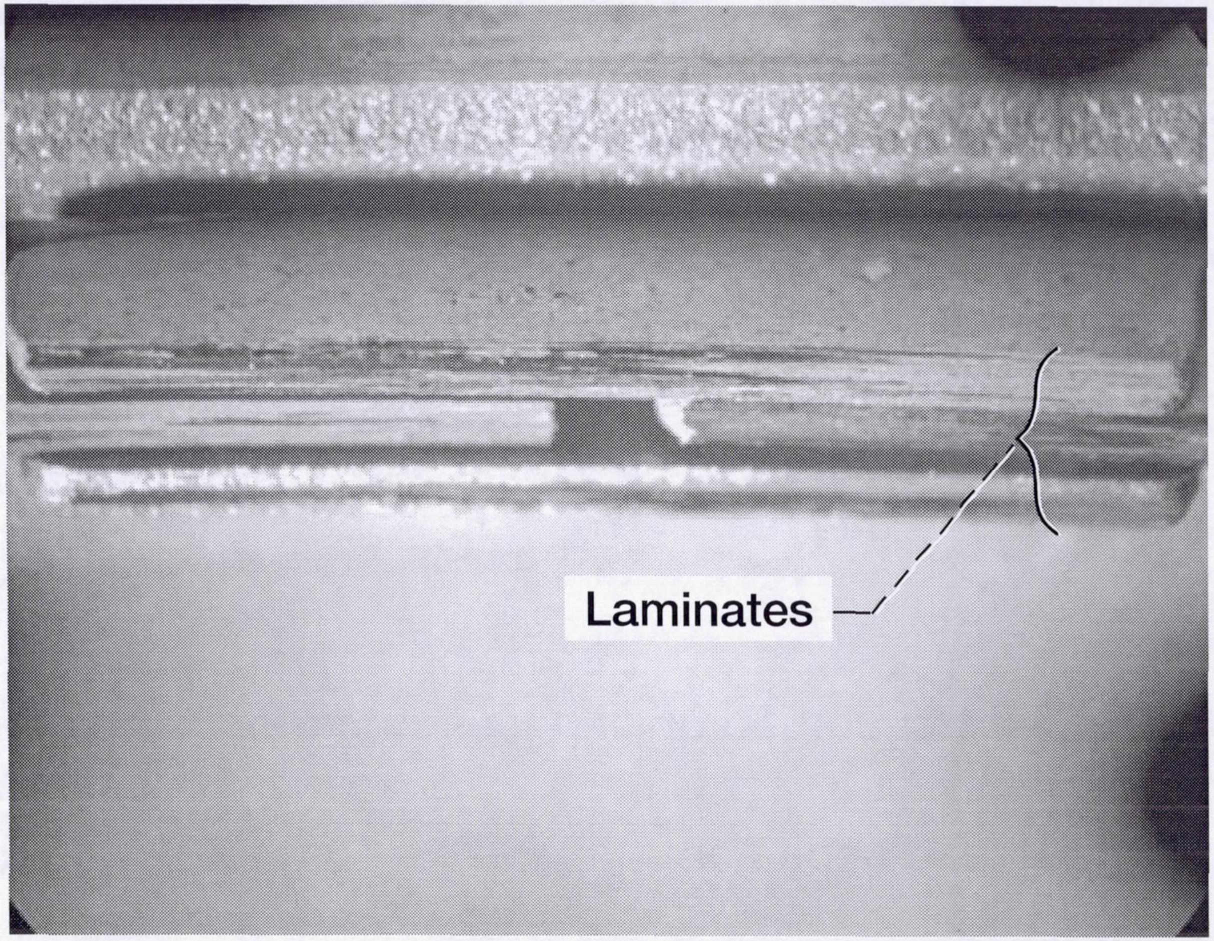
CD-99-79394

Magnified View of Upstream Finger Pad i.d. of Pressure Balanced Finger Seal Prior to Endurance Test



CD-99-79395

Magnified View of Upstream Finger Pad i.d. of Pressure Balanced Finger Seal After Endurance Test



CD-99-79396

Conclusions

1. Low cost photoetching fabrication technique demonstrated.

2. Pressure balanced finger seal design demonstrated very low hysteresis in repeated rig testing.

3. Finger seal air leakage is 20 to 70% less than a typical four-knife labyrinth seal with 0.005 inch radial clearance.

4. Finger seal operation demonstrated at: 778 ft/s, 60 psid and 1000 °F. and 945 ft/s, 80 psid and 800 °F.

5. Rotor-run out and endurance test results indicate finger seals have potential for long life applications.

6. Extensive analytical work and rig testing has resulted in a finger seal design that is ready for engine testing.

CD-99-79398

SEAL DEVELOPMENTS AT PERKIN ELMER FLUID SCIENCES

Tony O'Meara
Perkin Elmer Fluid Sciences
Warwick, Rhode Island

PerkinElmer™ fluid sciences.

CENTURION ™ MECHANICAL SEALS
PROVEN PERFORMANCE • RELIABLE SOLUTIONS

SEAL DEVELOPMENTS AT

PerkinElmer™
fluid sciences.

Tony O'Meara
15 Pioneer Avenue, Warwick RI 02888
(401) 781-4700
Tony.O'Meara@perkinelmer.com
October 1999

NAME CHANGE

12/98	Í Ò ®	Sealol EPD
01/99	Í Ò ®	Engineered Products CENTURION ™ MECHANICAL SEALS
10/99	PerkinElmer™ fluid sciences.	CENTURION ™ MECHANICAL SEALS

RESULTS OF NAME CHANGE

- A new legal entity under PerkinElmer Fluid Sciences
- No change to manufacturer's cage code
- No change to management, key personnel, or locations
- No change to processes or key contacts

R&D CONSOLIDATION

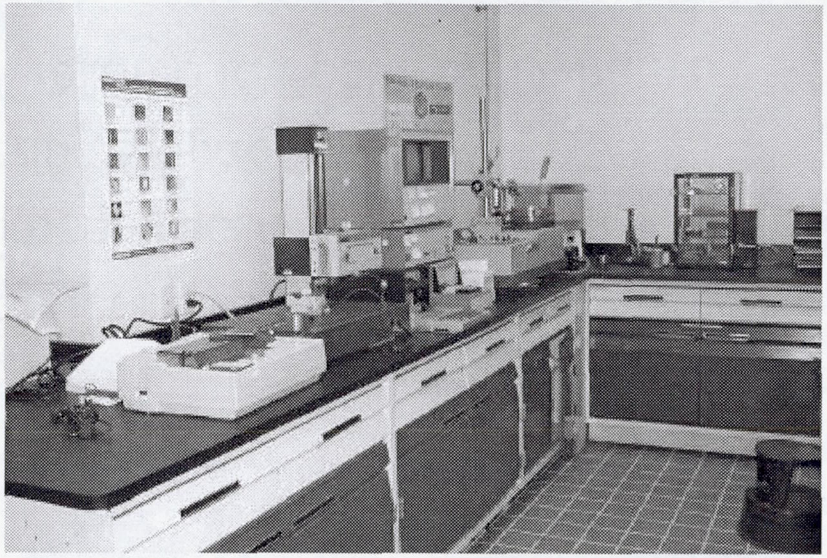
- R&D Facilities & Personnel consolidated at Warwick RI.
- 8/99 - Personnel Transition Complete
- 1/00 - New R&D Facility At Scheduled Completion

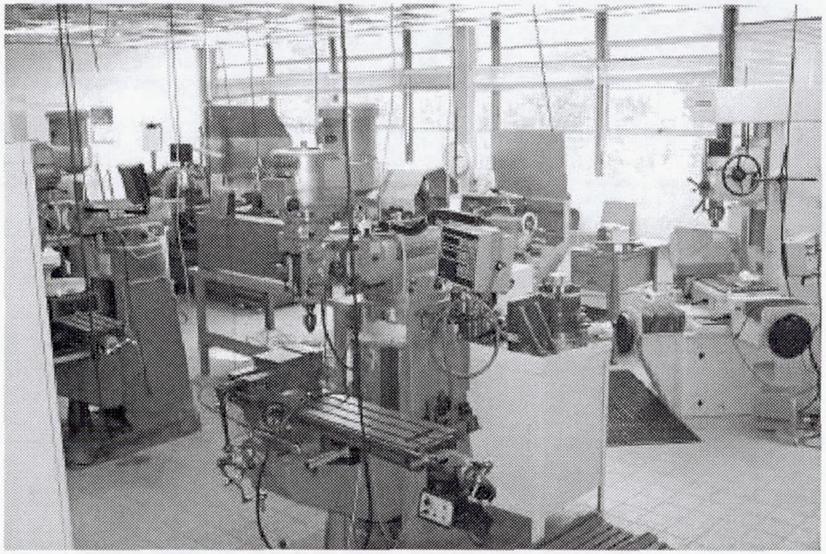
RESULTS OF CONSOLIDATION

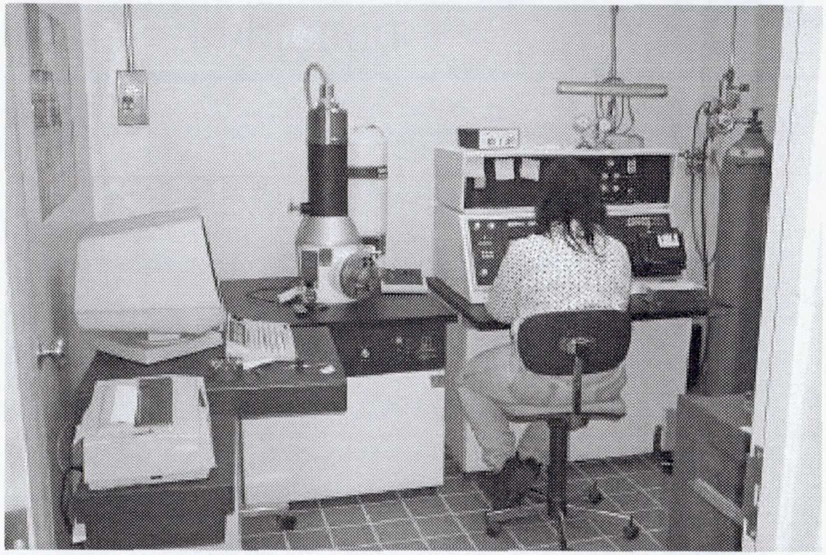
- Focused Dynamic Seal R&D / Product Development
- 4500 Sq.Ft New Product Development Facility at Warwick RI
- Enhanced Dynamic Seal Engineering Capability
- Enhanced Technical Resources Available to Focus on Dynamic Seal Vision / Goals

PerkinElmer™
fluid sciences.

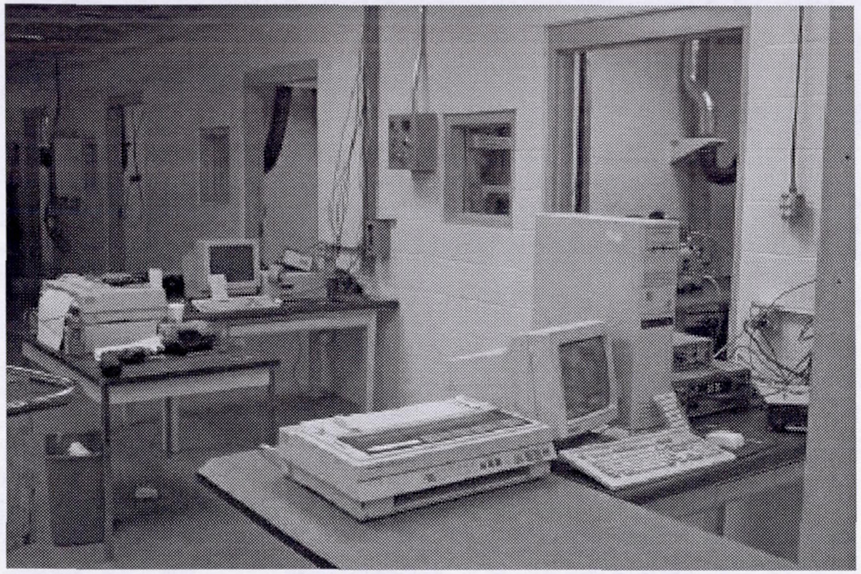
PRODUCT DEVELOPMENT FACILITY - Complete 1/1/2000

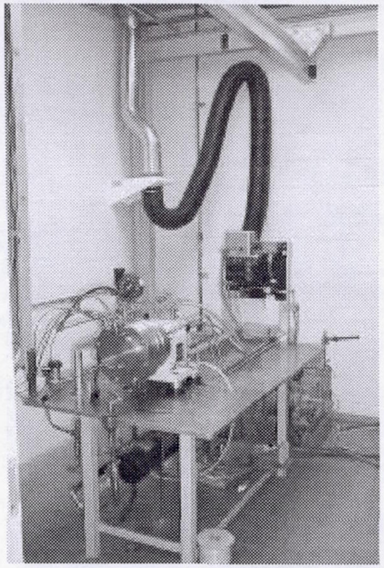


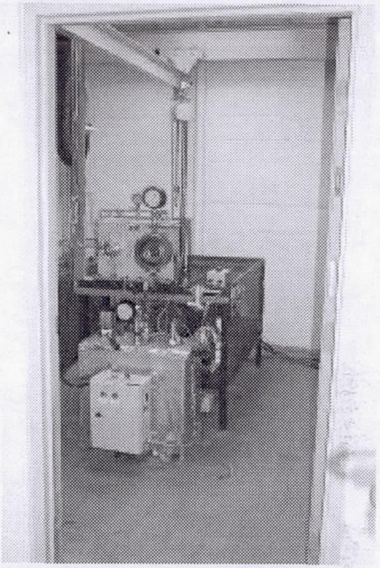


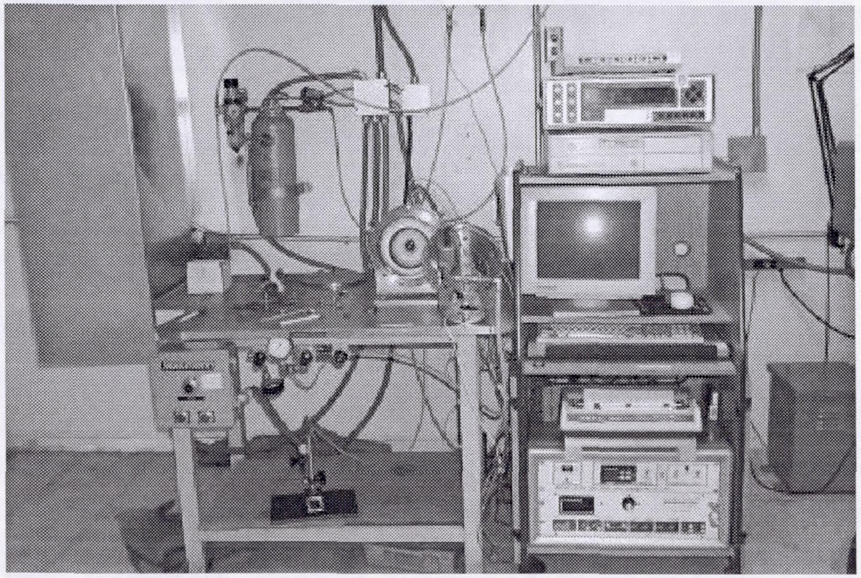


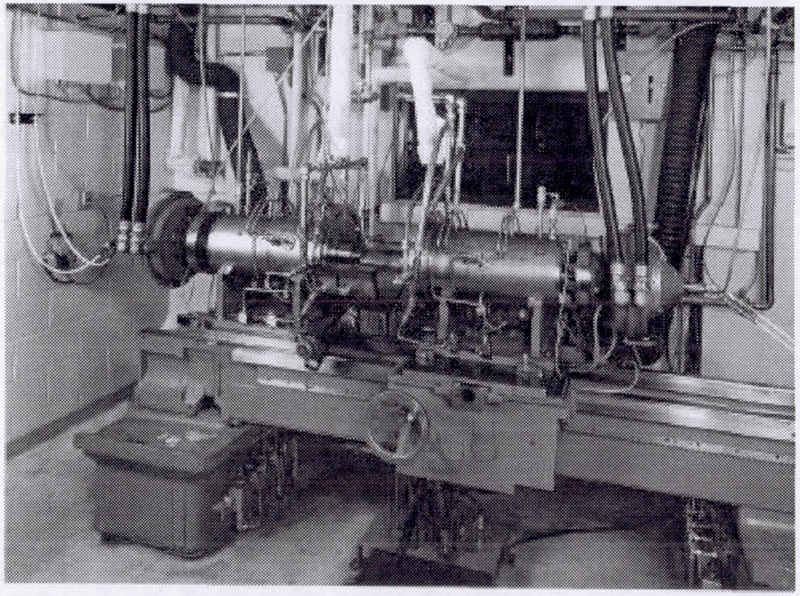
PRODUCT DEVELOPMENT FACILITY - Complete 1/1/2000











NASA/CP—2000-210472/VOL1

ENGINEERING

- Focus on Aerospace

- One Organization: Four Engineering Functions
    - Product Engineering
    - New Product Development
    - Test Engineering / Facilities
    - Materials Engineering

- Ongoing Commitment to New Product Development

- Emphasize Partnership Engineering
    - Build and Maintain Intimate Relationships with Major OEM Customers
    - Maintain On Site Presence at Customer Facility if Necessary
    - Active Participation in OEM *Preliminary* Design Process

TEST FACILITIES / TECHNICAL SERVICES

- Analytical Capability
  - **ANSYS** V5.3 Non Linear FEA
  - **ADINA** Structural Non Linear FEA / Computational Fluid Dynamics
  - Multiple Proprietary Design Codes, etc.

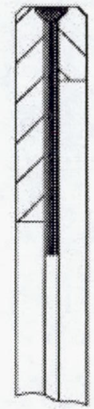
- Materials Laboratory Facilities
  - Full Complement of Optical examination equipment, Formscan, Tallysurf etc.
  - SEM with X-Ray Energy Despersive Analysis Capability
  - Thermal Analysis capability (TGA, DTA, DSC, TMA)

- Dynamic Seal Test Rigs Available

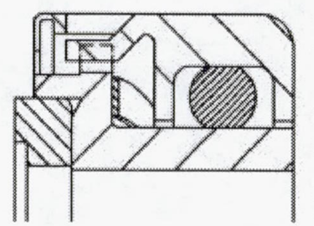
– ADV AERO RIG	25,000 rpm	120 psi	1000F	40 HP
– AERO RIG	36,000 rpm	100 psi	500F	20 HP
– HIGH SPEED RIG	45,000 rpm	100 psi	400F	25 HP
– GEARBOX RIG	20,000 rpm	500 psi	350F	50 HP
– HV RIG	51,000 rpm	145 psi	500F	
– SN1 RIG	15,000 rpm	145 psi	400F	
– TRIBOLOGY RIG	60,000 rpm		800F	

- PC Based Data Acquisition System (LabView)

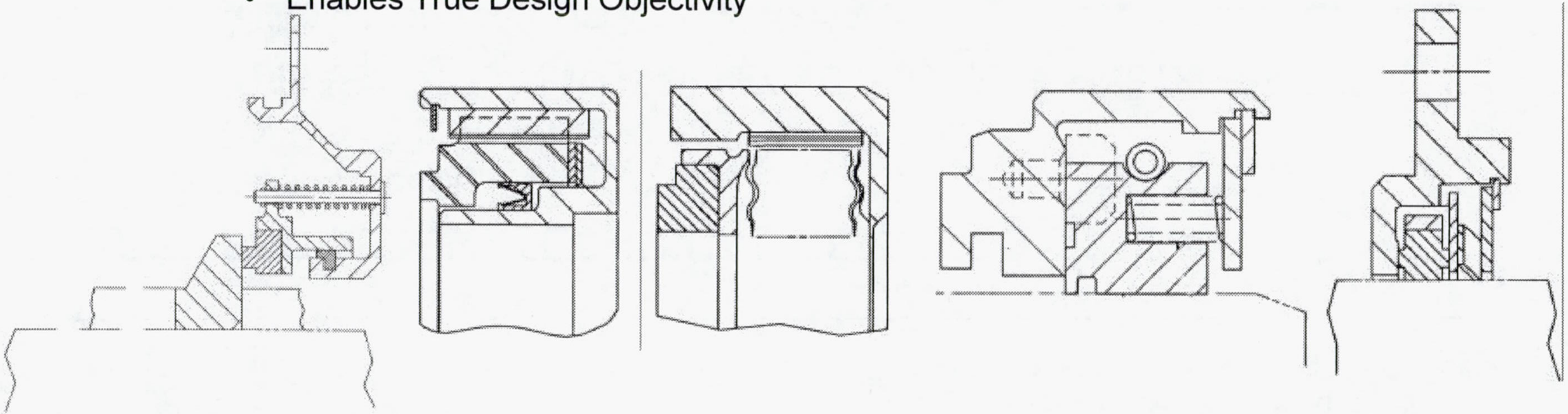
PRODUCT PLATFORMS



- Large Engine Mainshaft (Face)
- Small Engine / Accessory Gearbox Face Seals
- Bellows Face Seals
- Segmented Radial Seals (Contacting and Archbound)
- Clearance (Floating Ring) Seals
- Brush Seals

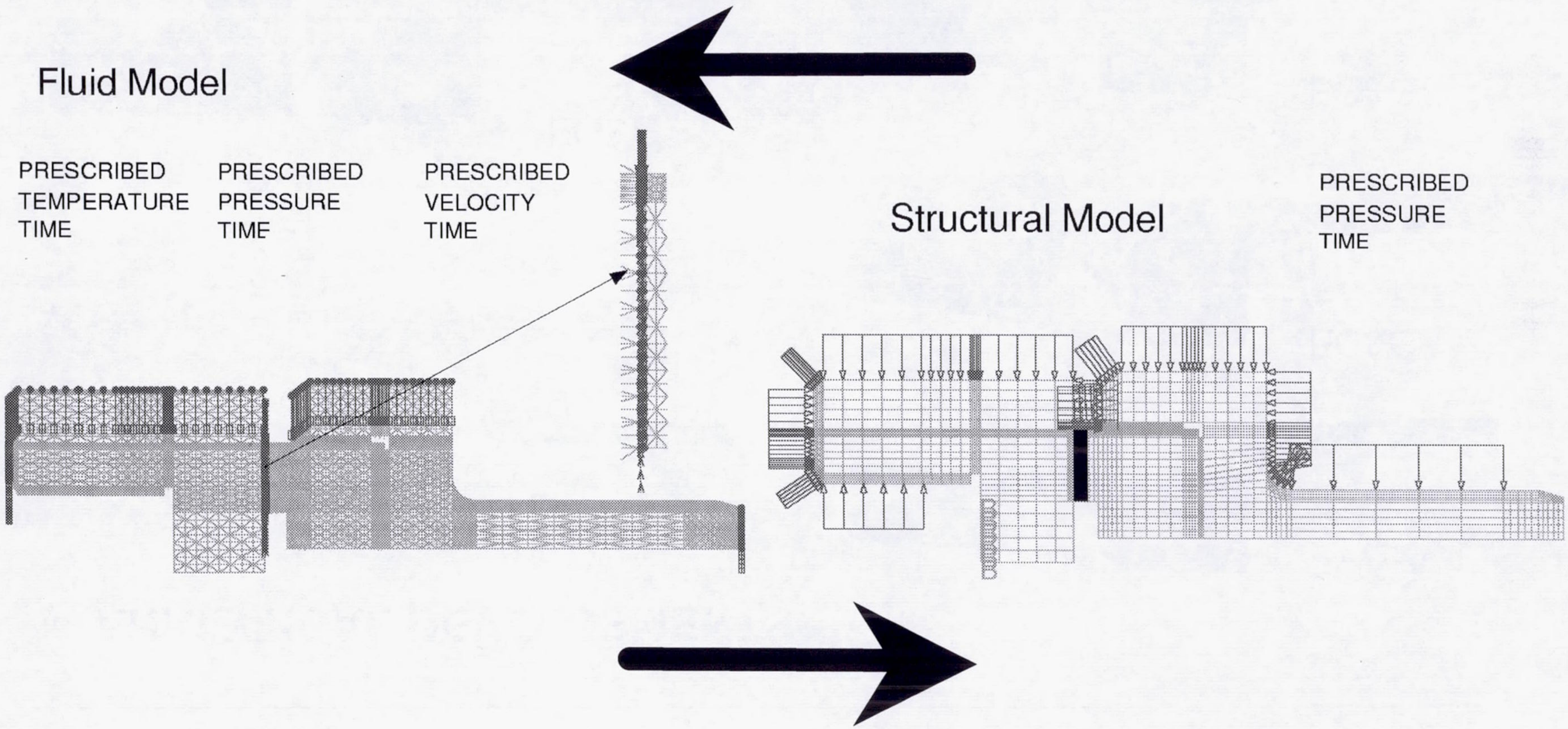


- Design and Manufacture Multiple Seal Configurations
  - Extensive Aerospace Qualifications Base for Each Platform
    - Enables True Design Objectivity



ANALYTICAL DEVELOPMENTS

- Structural / Fluid Modeling Capability



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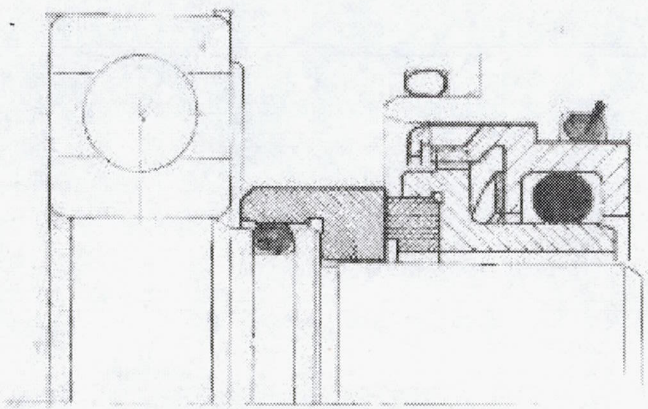
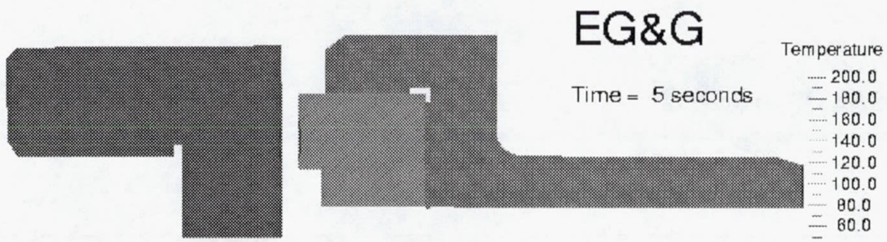
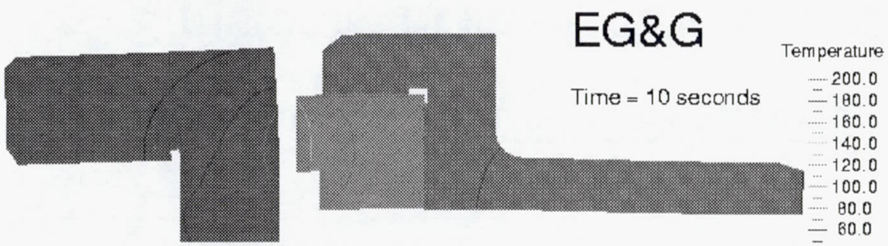
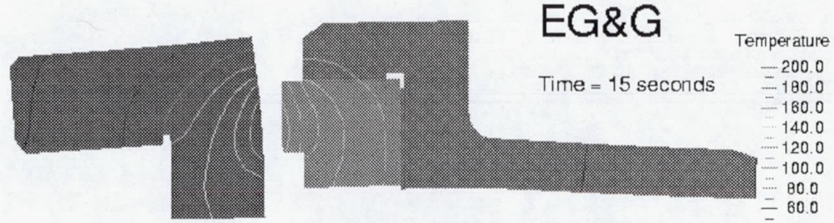
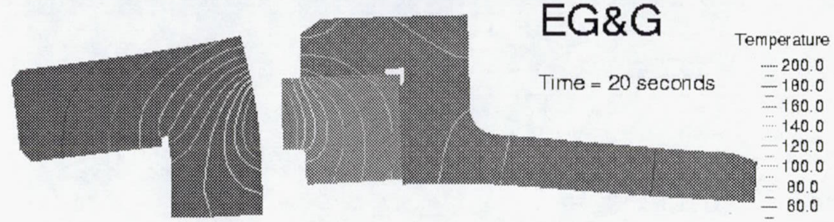
ANALYTICAL DEVELOPMENTS

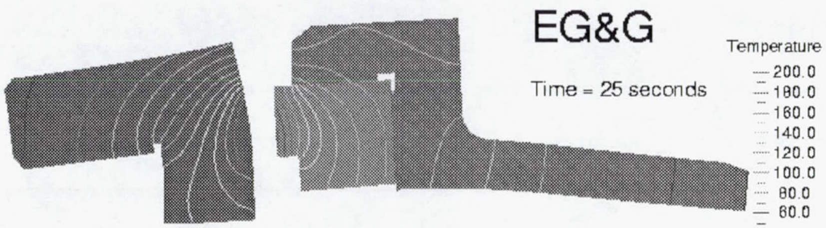


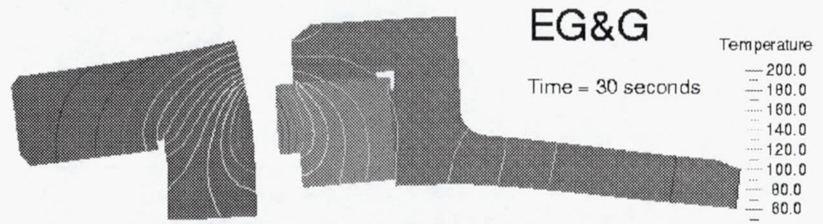






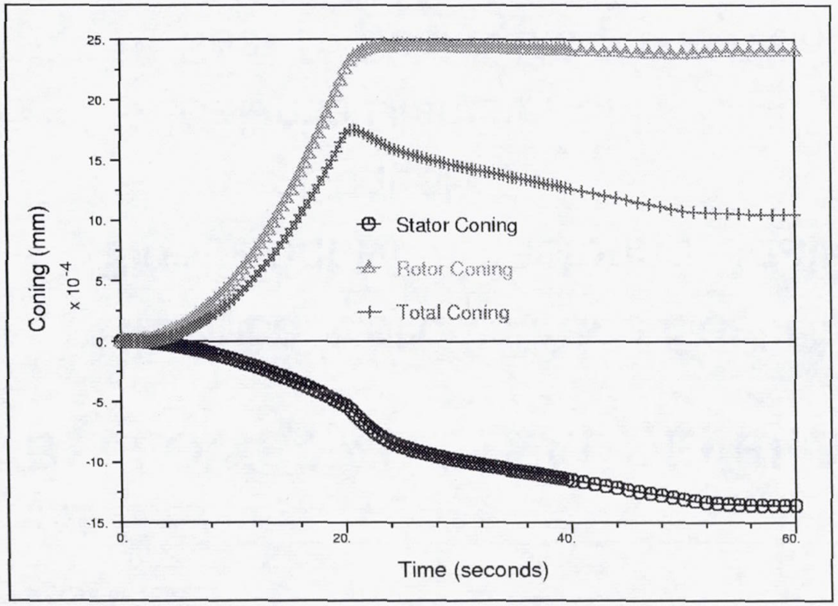


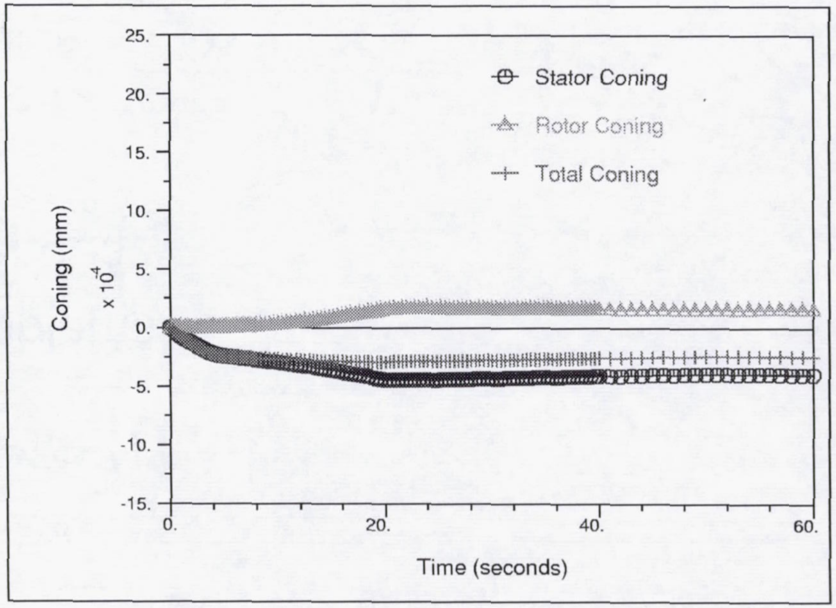




ANALYTICAL DEVELOPMENTS

- Face flatness and stability are critical for seal performance.
- Analytical techniques exist to model the behaviour of face seals.
- Face distortion can be minimised by design and selection of materials.
- Design / Analytical Optimization Significantly improves
- Seal Performance Design / Analytical Optimization Significantly improves Seal Performance





BELLOWS FACE SEAL DEVELOPMENT

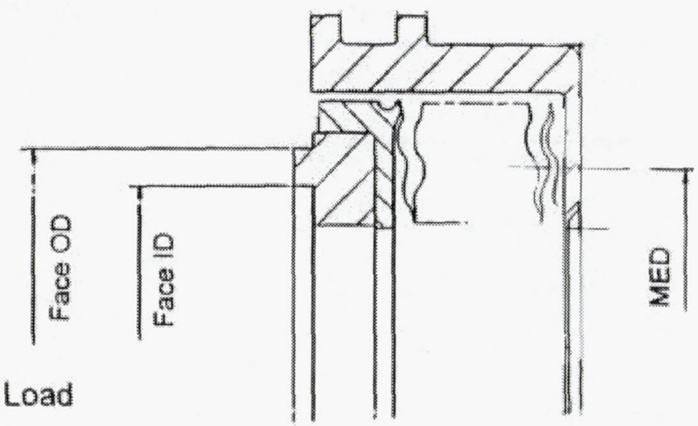
- Historical Bellows Face Seal Problems
- Significant Manufacturing Challenges
  - Load Control
  - Balance Diameter Shift
  - Seal To Seal & Lot To Lot Variation
- Manufacturing Capability Critical to Success

$$\text{MED} = \sqrt{(\text{Bellows ID}^2 + \text{Bellows OD}^2)/2}$$

Balance Ratio (ID Pressure): $$(B) = \frac{(\text{MED}^2 - \text{Face ID}^2)}{(\text{Face OD}^2 - \text{Face ID}^2)}$$

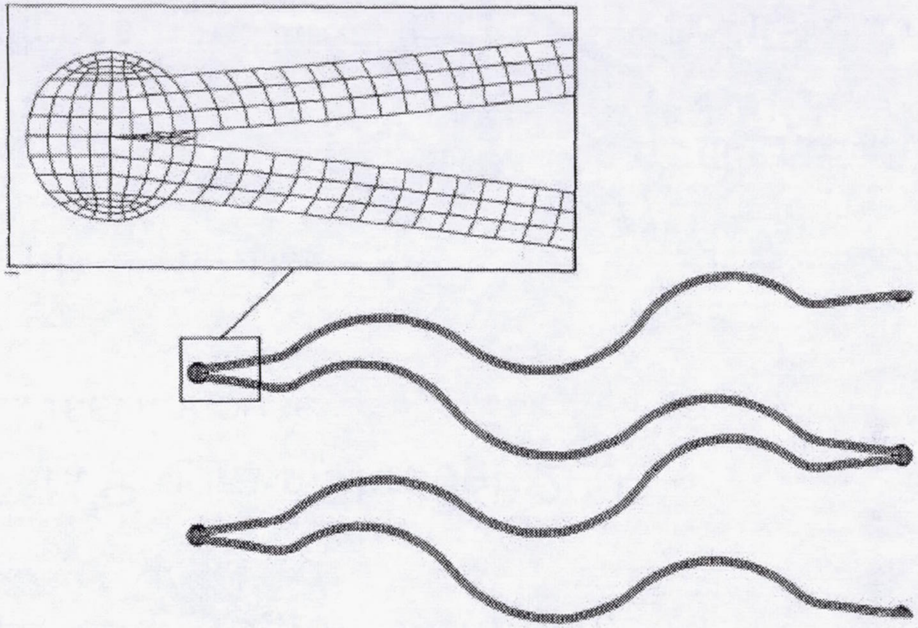
Balance Ratio (OD Pressure): $$(B) = \frac{(\text{Face OD}^2 - \text{MED}^2)}{(\text{Face OD}^2 - \text{Face ID}^2)}$$

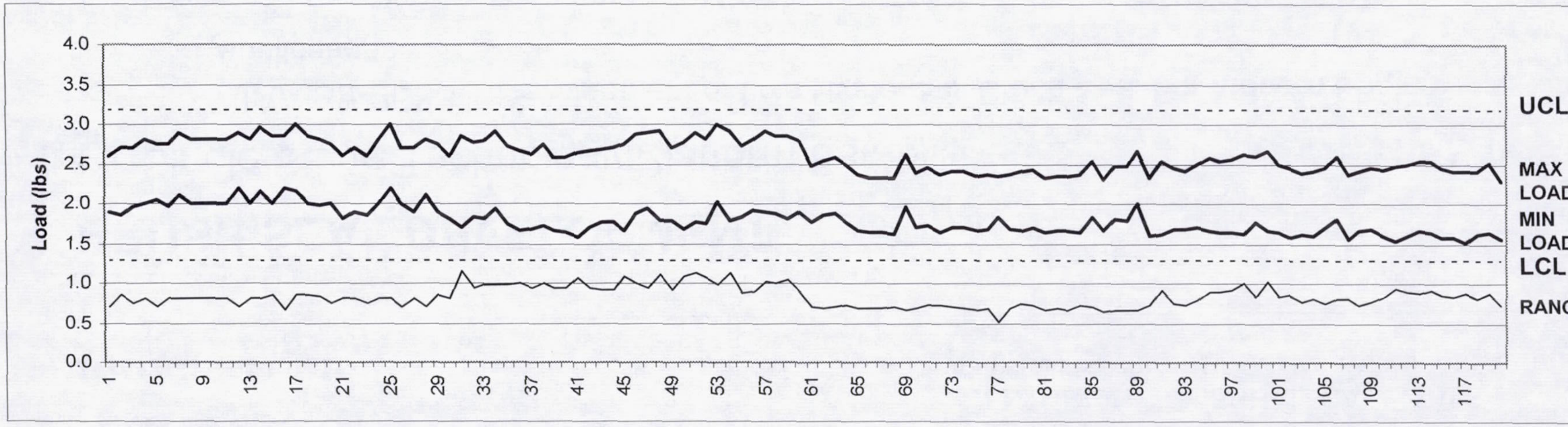
$$\text{Face Load} = [\Delta P \times (B - K) \times \text{Face Area}] + \text{Spring Load}$$



BELLOWS SEAL DEVELOPMENT

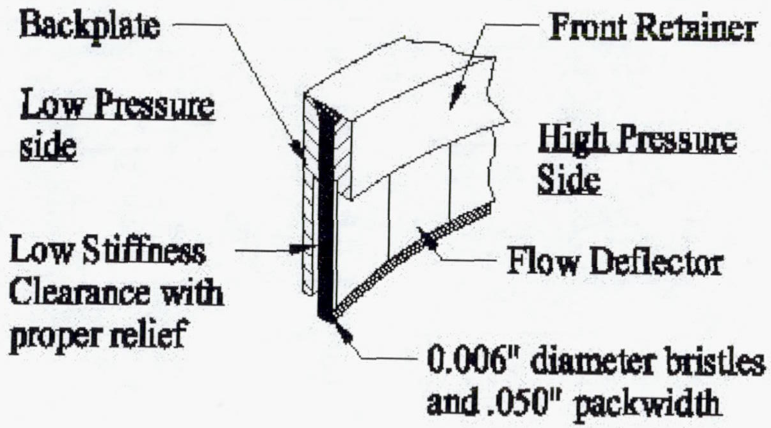
- Analytical Design Technique
  - FEA Optimization Tool Developed
  - CAM Manufacturing
- Bellows Cores Designed Specifically for each Application
- Minimized Part to Part Variation
- Proven Process
  - > 25 Designs Completed
  - Demonstrated Field Performance





BRUSH SEAL DEVELOPMENT

- Single Stage Technology Platform Established
  - AIAA 99-2683 - Development of Low Hysteresis Brush Seal For Modern Engine Applications
- Extensive Component Qualification Programs Completed
- High Temperature Development Program Through 2000
  - ATS Program with Siemens Westinghouse
- Turbine Rim Seal Development
- Performance Characterization
  - Pressure Effect of Bristle Stiffness
  - Measurement Technique
- Ongoing Emphasis on Manufacturing

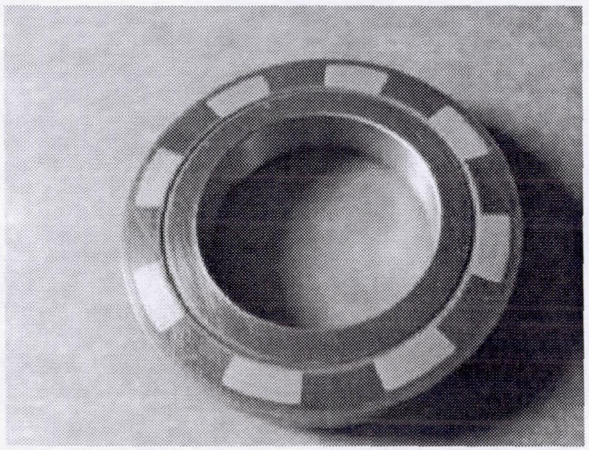


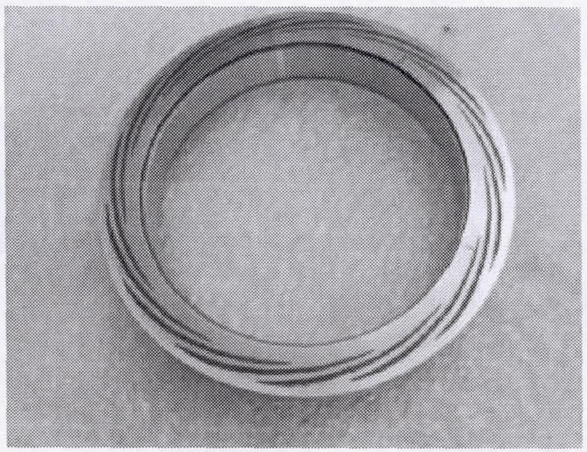
PerkinElmer™ fluid sciences.

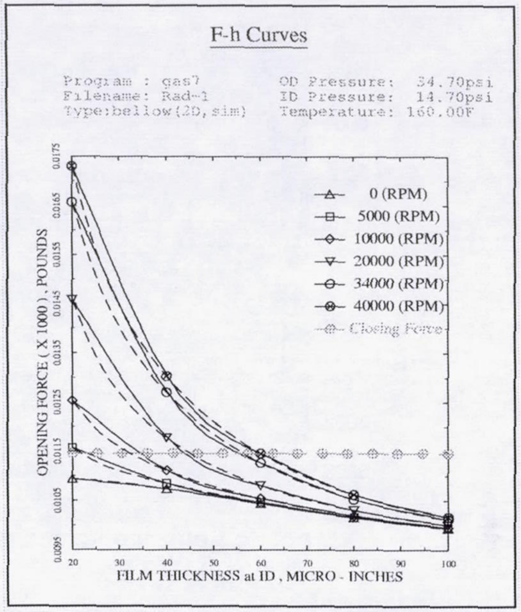
CENTURION ™ MECHANICAL SEALS
PROVEN PERFORMANCE • RELIABLE SOLUTIONS

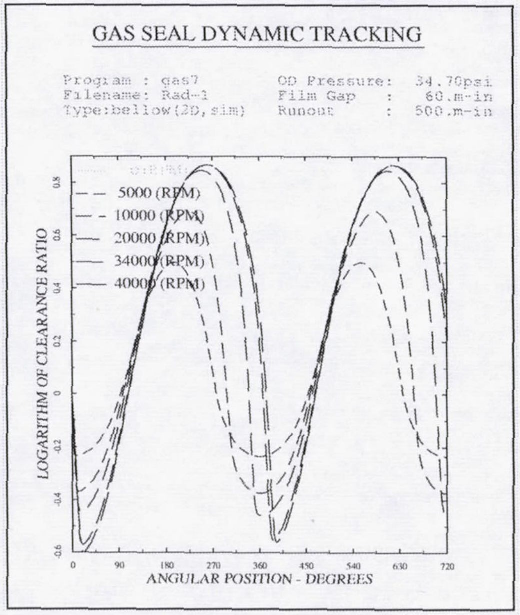
HYDRODYNAMIC FACE SEAL

- 10+ Years Industrial Seal Experience
- Developed for Axial Air / Oil Seals for Aerospace
  - Small Gas Turbine Mainshaft
  - Accessory Gearbox
  - AIAA 99-2822 - Development of Liftoff Seal Technology for Air/Oil Axial Sealing Applications
- GAS6b Design Code
  - Modified For Dynamic Tracking
  - Integrated FEA Capability





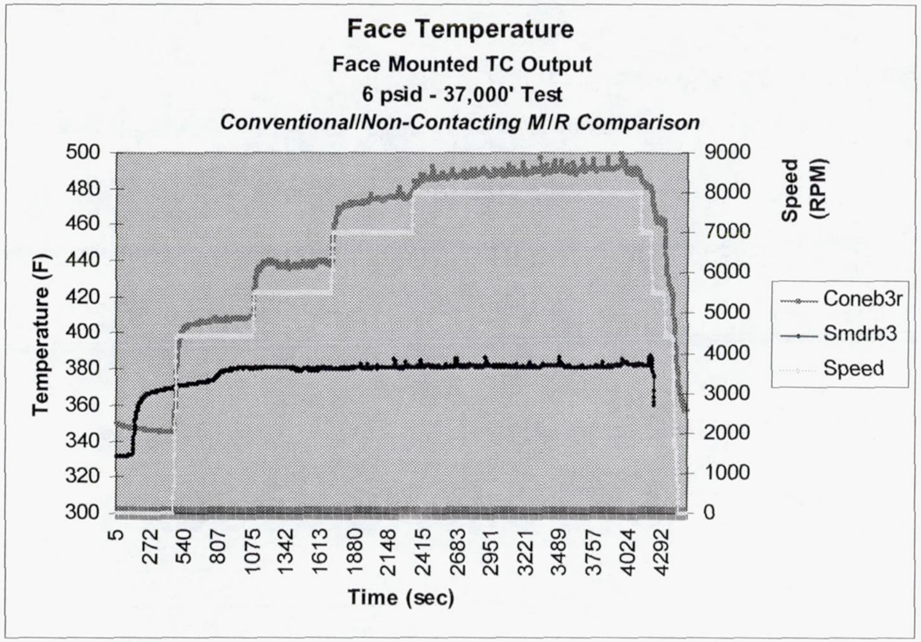




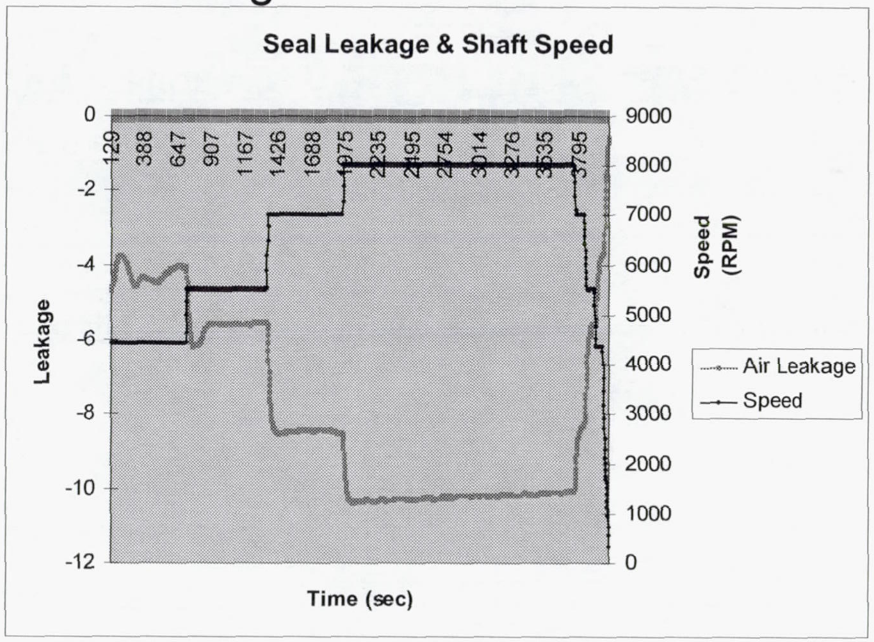
HYDRODYNAMIC FACE SEAL

- Design Code Validation Ongoing
- Characterization Program in Process
- Application Specific Test Programs

Lift Off

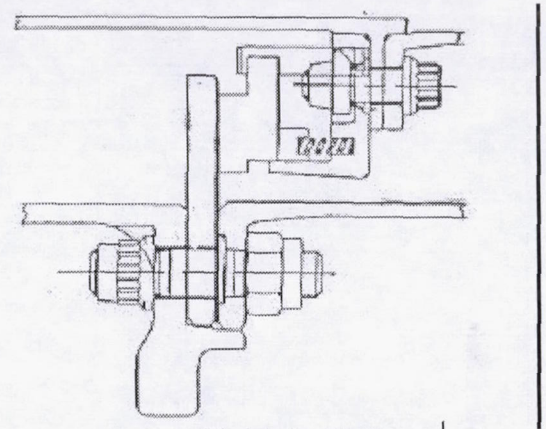


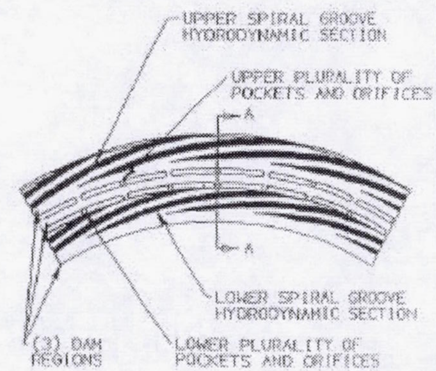
Air Leakage

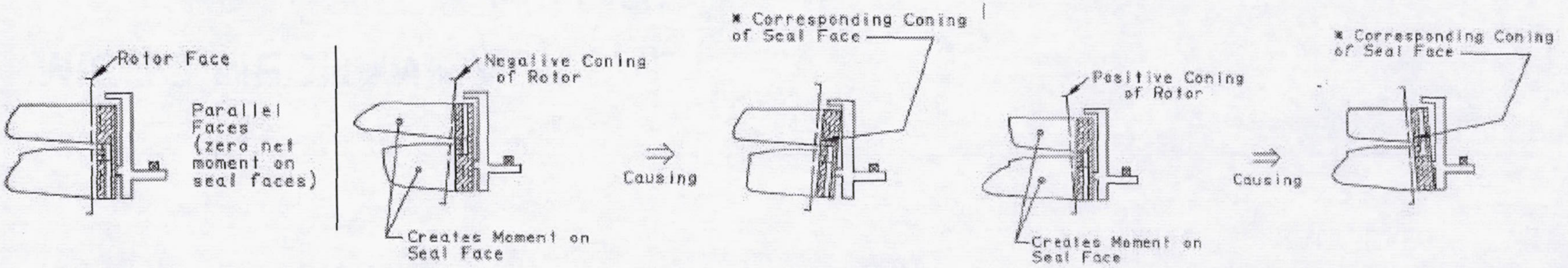


ADVANCED HYDRODYNAMIC FACE SEAL

- High Speed, High Temperature Air Seal
  - Joint Development: RR Allison, USAF
- AIAA 99-2684 - Development of a High Speed, High Temperature Compressor Discharge Seal
- Revised Design based on Initial Test
- Program Ongoing Through 2000
  - Design Optimization Based on Initial Testing
  - Tribology Testing

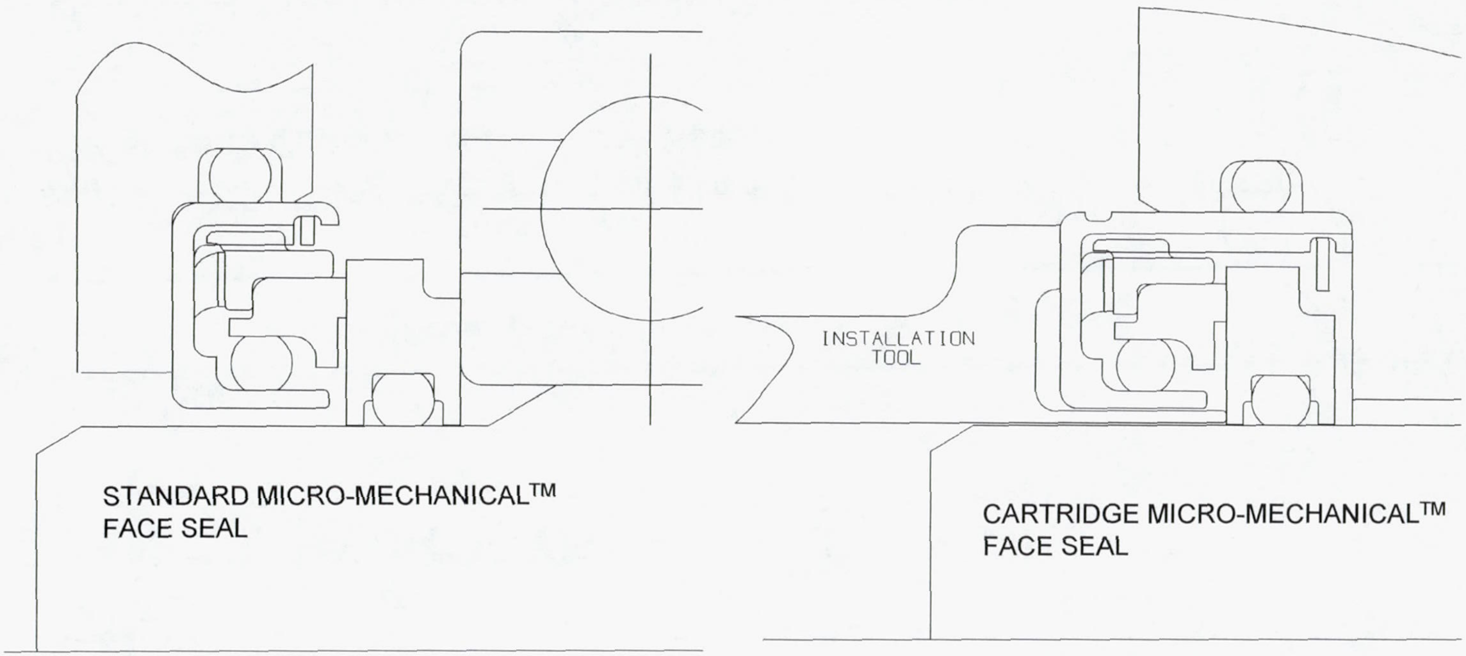






MICRO-MECHANICAL SEAL

- Developed for Specific Gearbox 'Problem' Applications
- Reduced Axial / Radial Space Requirement
- Retro Fit Capability



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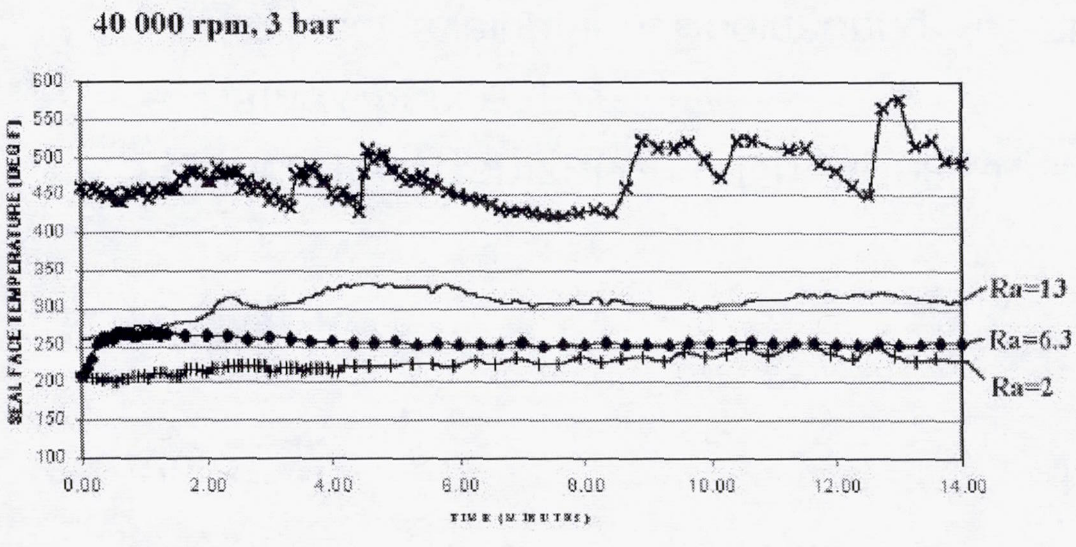
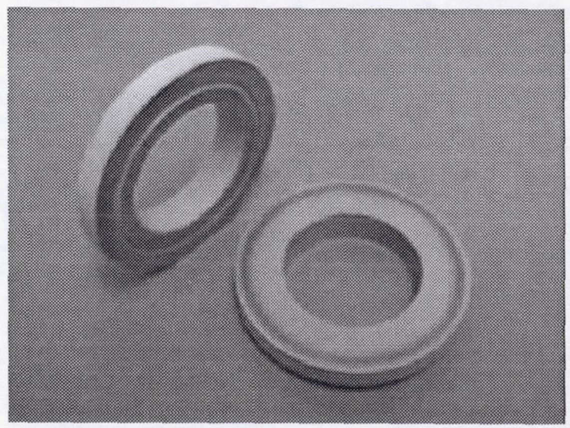
MATERIALS DEVELOPMENT

- Full Time Materials Engineering + Technician
- Comprehensive Material Characterization Program Ongoing
  - Collaborative with OEM's
- Generate Performance Characteristics Database:
  - Existing 'Traditional' Tribopairs
  - 'New' Tribopairs





IN SUMMARY......

- Significant Organizational Changes Over recent months
  - Name Change
  - Product Development Engineering Structure

- Multiple Dynamic Seal Product Platforms

- Committed to New Product Development

- Excellent Engineering & Technical Support Capability

- Committed to building Technical Relationships

ADVANCED ASPIRATING SEAL

Alan D. McNickle
Stein Seal Company
Kulpsville, Pennsylvania

Advanced Aspirating Seal

Stein Seal Company

Presented at:

NASA - Glenn Research Center
Seal/Secondary Air System Workshop
Cleveland, OH
October 28 & 29, 1999

Presented by:
Alan D. McNickle, P.E.
Phone: (215) 256-0607, ext. 206
Fax: (215)-256-4818
e-mail: mailbox@steinseal.com

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NASA99.PPT
1

Stein Seal Company is developing and testing an improved 14.7" aspirating seal for GE gas turbine compressor discharge applications. The aspirating seal provides hydrostatic operation with low leakage and high gas film stiffness at high differential pressures and high temperatures. This all metal seal has the ability to operate at high temperature with large rotor runout. The design process and comparison to the original aspirating seal will be discussed along with recent test data.

Advanced Aspirating Seal

Outline

- Design Goals & Operating Conditions
- Seal Operation & Evolution
- Analysis - Original & Advanced Seal Design
- Rig Test Results
- Performance Attained

Goals/Objectives

- Develop Advanced Aspirating Seal (IHPTET/JSF Engine)
  - 14.7″ & 36″ seal
- Meet Leakage and Performance Goals
- Increase Gas Film Stiffness
- Increase Seal's Ability to Follow Extreme Rotor Runouts
- Increase Seal Operating Speed
- Build & Test 14.7″ Seal

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2

The advanced aspirating seal is being developed by Stein Seal Company for GE Aircraft Engine. The advanced seal offers improvements beyond the original aspirating seal design built several years ago.

Two seal sizes were studied and include a 14.7" seal and a 36" seal. The 14.7" seal was built and tested. The 36" seal was designed but not built.

The topics for discussion and program goals/objectives are included above.

Advanced Aspirating Seal

Requirements / Challenges / Application

Operating Conditions:
- Shaft Speed: 365 ft./sec.
- Press. Diff.: 100 psid
- Air Temp.: 750 °F
- Leakage: ~ 1.25 scfm/psid
- Seal Life: Unlimited (non-contacting seal)

Challenges:
- Improve gas film stiffness
- Maintain uniform gas film clearance during all conditions
- Maintain low leakage performance
- Provide infinite seal life
- All metal design

Applications:
- Turbine Rim Seal
- Compressor Discharge

Funding:
- Provided by GE Aircraft Engine
  - Developed under NASA's AST program (Glenn Research Center)
    - » IHPTET initiative

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3

The operating conditions are shown and are representative for the 36" seal.

The seal is developed under NASA's AST program and funded by GE Aircraft Engine (Cincinnati)

The advanced seal requires an improvement to the gas film stiffness as compared to the original seal. Low leakage and uniform gas film clearance are requirements for the all metal seal design.

The advanced aspirating seal is targeted for Turbine rim seal and Compressor discharge applications. The aspirating seal is a replacement for brush seals and has significant leakage improvement as compared to brush seals. The aspirating seal leakage is approximately 20% of a brush seal.

Advanced Aspirating Seal

Aspirating Seal Evolution

1989 - 1996

Original Aspirating Seal

- 14.7” (Tested at Stein)
  - .400” air bearing
  - .100” dam
  - .150” trench
- 36” (Tested at GE CRD)
  - .440” air bearing
  - .100” dam
  - .160” trench

1996 -1999

Advanced Aspirating Seal

- 14.7” (Tested at Stein)
  - 1.25” air bearing
  - .250” dam
  - .450” trench
- 36” (Analysis performed)
  - .550” air bearing
  - .050” dam
  - .180” trench

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This slide shows the physical parameters for the aspirating seal that have been developed during the last ten years.

The original seal designs are characterized by narrow seal dams and narrow air bearing faces. The advanced aspirating seal has wide seal dams and wide air bearing faces. This yields improvements to the gas film stiffness.

The trench area is an annulus that separates the seal dam from the air bearing.

Advanced Aspirating Seal

Development Efforts
Two Seal Sizes Developed:

Sub-Scale Seal

- 14.7" Seal (Rig Seal)
  - Optimized design
  - For rig testing at Stein
  - Utilizes highest gas film stiffness within GE-90 rotor envelope
- Rotor flow diverter <u>not required</u>

Full Size Seal

- 36" Seal (Paper study)
  - Seal targeted for GE CRD test rig
  - Utilizes existing rig rotor with changes
- Rotor flow diverter <u>is required</u>

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<u>14.7" seal</u>

This seal has the widest face configuration that fits the GE-90 rotor envelope. The gas film stiffness is greatly improved compared to the original aspirating seal. This seal configuration was chosen for rig tests due to the performance increase.

The flow diverted is not required on the rotor.

<u>36" seal</u>

This seal has a radial face configuration that fits the existing rig rotor face on the GE CRD rig. This seal was developed to demonstrate that an improved aspirating seal could be developed to fit an existing test rig. This seal , to date, has not been built.

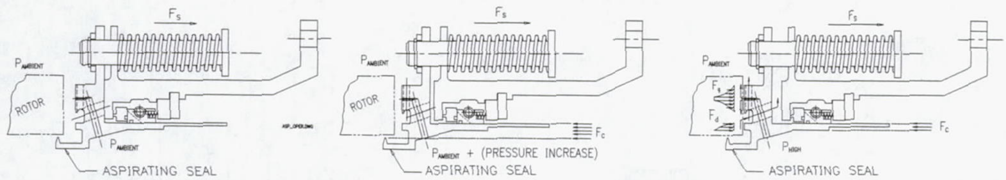
<u>Rotor flow diverter</u>

The rotor diverter is a piece of the rotor that projects into the trench (annulus) between the seal dam and air bearing. Although the rotor flow diveter is not required on the 14.7" seal, the flow diverter operation directs the seal dam gas flow into the radial and axial vent slots. Without the rotor flow diverter the seal may have a tendency to not establish the proper gas film since air from the seal dam discharge tends to exit radially and disrupt the gas flow on the air bearing.

Advanced Aspirating Seal

Seal Operation

Force Balance Equation, Fc = Fg + Fd + Fs + Inertia + Friction



START-UP / SHUT-DOWN: (0 PSID)

- Seal is retracted open by springs
- Gap exists between seal and rotor face

AT PRESSURE INCREASE: (< 5 PSID)

- Seal is still retracted open by springs
- Pressure increases and seal starts to close towards rotor.
    - Pressure drop occurs across balance dia. and laby tooth
    - Closing force overcomes retraction spring and friction forces
- Gap between rotor and seal face decreases

WITH PRESSURE DIFFERENTIAL: (> 5 PSID)

- Seal moves toward rotor as pressure continues to build
    - Retraction spring force, friction force, and inertia forces are overcome
- As seal approaches rotor
    - Pressure drop occurs across seal dam
    - Air bearing force is established
- Laby tooth is no longer the primary pressure breakdown mechanism
- Seal is in equilibrium (1.5 to 2.0 mils gap)
    - Closing forces = Opening forces

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The seal operation is characterized by a non-contacting seal.

Start up / Shut down:

At rest, the seal is retracted open by springs. This pulls the seal away from the rotor. At this position the seal has no pressure drop across the seal.

At pressure build up:

As pressure builds, the closing force starts to increase, overcoming the retraction spring forces and the friction and inertia forces. The pressure force is established by the area created by the balance diameter and the laby tooth (located beneath the rotor.)

At full pressure:

The seal is in equilibrium at 1.5 top 2.0 mils. The closing force equals the opening force. The closing force is established by the area created by the balance diameter and the seal dam ID. The opening force is created by the air bearing force. This force tends to open the seal.

Advanced Aspirating Seal

Work Performed

- Parametric Studies
  - Studied seal performance effects with varied seal features:
    - » Seal dam, gas bearing, & trench geometry
- Gas Bearing Analysis & Rig Tests
  - Analysis performed by Wilbur Shapiro, Inc.
    - » NASA GFACE Code
  - Rig tests validated analysis
- Optimized Design Features:
  - 36" Seal: .550" gas bearing, .050" dam, .180"trench
  - 14.7" Seal: 1.250" gas bearing, .250" dam, .450" trench
- CFD Analysis (CFDRC Corp.)
  - Performed on 14.7" & 36" seals
    - » 14.7" Seal: Rotor flow diverter not required
    - » 36" Seal: Rotor flow diverter required
    - » Operating Gap: .0015" to .0020"

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7

Parametric design studies looked at all possible seal configurations that would show improve d performance as compared to the original aspirating seal. Features that affect seal performance include:

Size and placement of the seal dam and air bearing

Number of air bearing holes, hole diameter, and number of rows of holes, and hole spacing

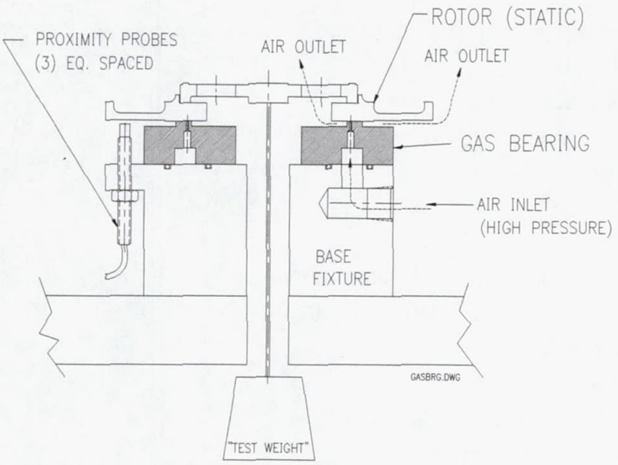
Gas bearing analysis and static rig tests were performed to determine the gas bearing performance. The actual rig tests were used to correlate the NASA GFACE seal code and Coefficient of Discharge, Cd.

The optimized seal configurations for both seal sizes are shown. The 14.7" seal has the widest radial face as it has the optimum gas bearing stiffness per unit length. The 36" seal fits the existing rig rotor at GE CRD.

Computational Fluid Dynamics (CFD) was performed on both seal sizes. CFDRC of Huntsville, Alabama, performed these studies. Conclusions showed that the rotor flow diverter was required on the 36: seal but not required on the 14.7' seal. The seals operate properly with a gas film of 1.5 to 2 mils.

Advanced Aspirating Seal

Static Gas Bearing Rig



- Provides data for Pressure vs.:
  - Load capacity
  - Film clearance
  - Leakage
- Data used to validate NASA GFACE code
- Static rig permits quick bearing change-outs for alternate bearing faces:
  - Multiple orifice rows
  - Orifice hole size and spacing

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Static gas bearing test rig for sub-scale testing.

The rig is used to collect information such as:

Leakage vs. pressure

Film clearance vs. pressure

Proximity probes measure the gas film clearance.

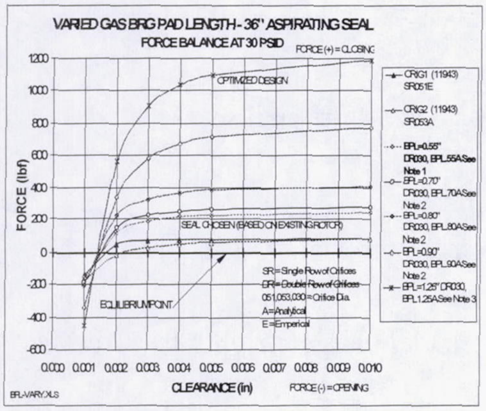
Gas flow in inward. The test weight simulates the seal closing force at the rated pressure differential.

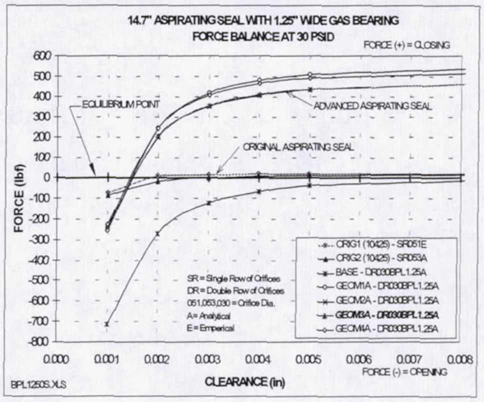
The data form this test rig is used to correlate the NASA GFACE seal code.

Advanced Aspirating Seal

Analysis - Force vs. Clearance

14.7" & 36 " Seals





- Advanced seal has steep slope at equilibrium point for:
  - Slope vs. Clearance
- Original seal has shallow slope
- Steep slope yields improved gas film stiffness

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Aspirating seal operates at an equilibrium point where the gas film is maintained at 1.5 to 2.0 mils.

Seal equilibrium point is where Force = 0 lbf. on the Y-axis. The operating gas film clearance is determined where the curve line cross the equilibrium point.

Steep line slopes are desirable since any change in clearance is a correspondingly high change in force.

The original aspirating seal configuration (solid circle) has a less steep slope as compared to the improved aspirating seal configuration (open triangle).

Gas bearing face width comparison:

.440" Original aspirating seal design

1.250" Improved aspirating seal design

Gas film stiffness improvements are gained compared to the original seal design:

14.7" seal: 5.5 : 1 greater stiffness vs. original seal

36" seal: 1.7 : 1 greater stiffness vs. original seal (dictated by rotor size)

36" seal (optimized design): 6 : 1 greater stiffness vs. original seal

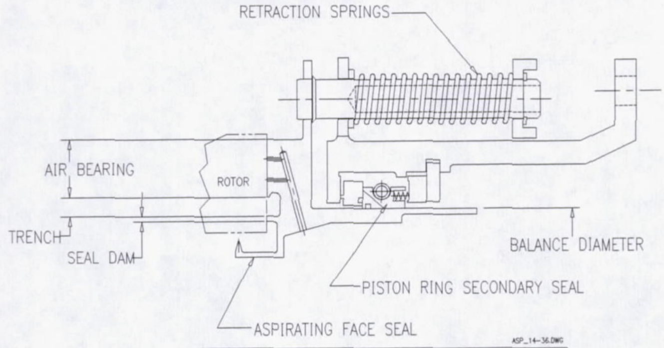
Advanced Aspirating Seal

Analysis - Air Bearing Stiffness Comparison

- Improved Gas Film Stiffness (based on 30 psid)
  - 14.7" Advanced Seal Stiffness 5.48 > Original Seal
  - 36" Improved Seal Stiffness 1.67 > Original seal
    - » Seal fits existing rig rotor face
  - 36" Advanced Seal Stiffness 6.02 > Original seal
    - » Optimized design
- Improved Seal Stiffness Benefits:
  - Permits seal to follow extreme rotor runouts
  - Improved load support
  - Small film clearance changes yield larger "righting" force balance

Advanced Aspirating Seal

Seal Dimensions - 14.7" & 36"



ASP_14-36.DWG

DIMENSION	SEAL SIZE	
	14.7"	36"
AIR BEARING WIDTH	1.250"	.550"
TRENCH	.450	.180"
SEAL DAM	.250"	.050"
BALANCE DIAMETER	14.700"	36.160"
ORIFICE DIA	.030"	.030"
ORIFICE SPACING	.828"	.806"
NUMBER OF ROWS	2	2

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Physical comparison between the 14.7" and 36" aspirating seals.

The balance diameter defines the nominal seal size.

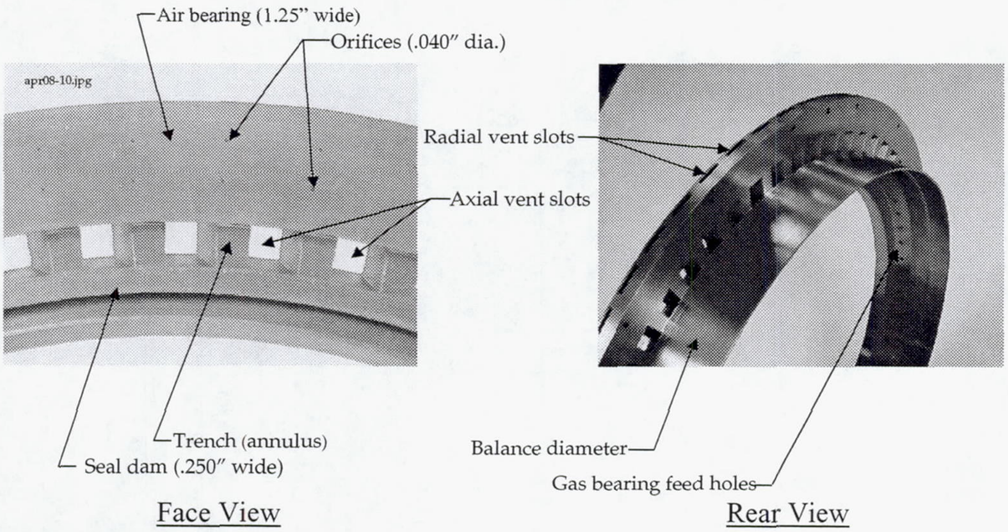
The gas bearing for the 14.7" seal offers the best gas film stiffness improvement as compared to the original aspirating seal.

The gas bearing for the 36" seal is the best size that fits the existing test t rig rotor at the GE CRD facility. If space permitted a larger rotor, then a wider gas bearing face would be utilized.

Each seal has a double row of gas bearing orifices for optimum gas film stiffness for the space permitted.

Advanced Aspirating Seal

Seal Features - 14.7" seal (during mfg.)



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The photographs show the 14.7" aspirating seal features.(taken during fabrication)

Material: 410 stainless steel

Advanced Aspirating Seal

Rig Tests

1. Gas Bearing Static Tests
2. Gas Film Calibration / Verification
   - Assess bearing supply pressure to orifice
   - Establish film clearance at operating pressure
3. Performance Mapping
   - Static/Dynamic tests
   - Speed and Pressure traverses
4. Rotor Runout Tests
   - 5 mil & 10 mil rotor (one per rev)
5. Max Conditions
   - GE-90 Conditions
6. Sand Ingestion
   - 0 to 10 micron particle size, 1/3000 lb/sec flow rate

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A series of rig tests are planned to assess the seal performance at engine conditions.

Rig tests for the 14.7' seal are performed on a dynamic test rig at Stein Seal Company.

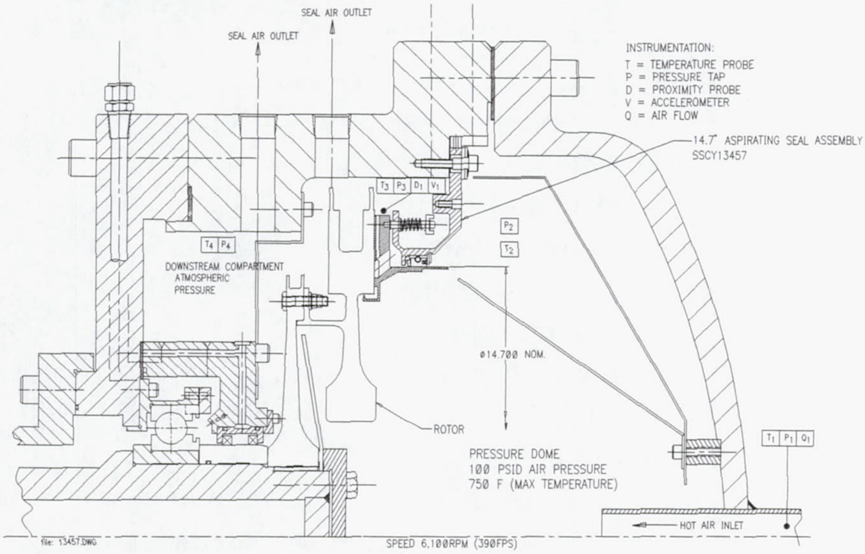
Gas film calibration tests are used to assess the leakage performance with fixed film clearances between the rotor and seal face. Clearances are achieved by the use of shim stock material that is cemented to the rotor face at equidistant positions.

Rotor runout tests are performed to simulate gas turbine rotor whirl on a "one per rev" cycle.

Proximity probes measure the gas film clearance.

Advanced Aspirating Seal

Dynamic Test Rig - 14.7” Aspirating Seal



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Dynamic test rig for the 14.7” sub-scale seal.

During operation the high pressure air enters the rig pressure dome through the air inlet pipe at the far right side. At 0 psid the seal is retracted open by mechanical springs, pulling the seal away from the rotor leaving a .090” gap. As pressure builds to approximately 3 to 4 psid, the seal is aspirated closed towards the rotor, overcoming the retraction spring force and piston ring friction force. The gas film is established between the rotor and seal face; 1 to 2 mils.

The mechanism to close the seal is a pressure force developed by the area projected by the balance diameter and laby tooth diameter.

<u>Test conditions:</u>

Shaft speed: 6,100 rpm (390 fps)

Pressure differential: 100 psid

Temperature (max.): 750 ^{0}F

<u>Seal configuration:</u>

.250” wide seal dam

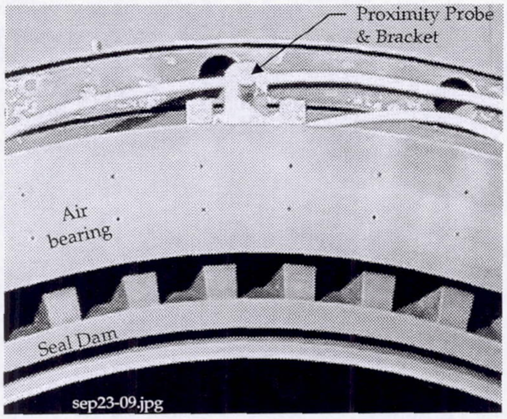
1.250” wide gas bearing

(2) rows of .030” dia. orifices

.450” wide trench (annulus between the seal dam and air bearing)

Advanced Aspirating Seal

Instrumented Seal - 14.7" seal



Seal Face View

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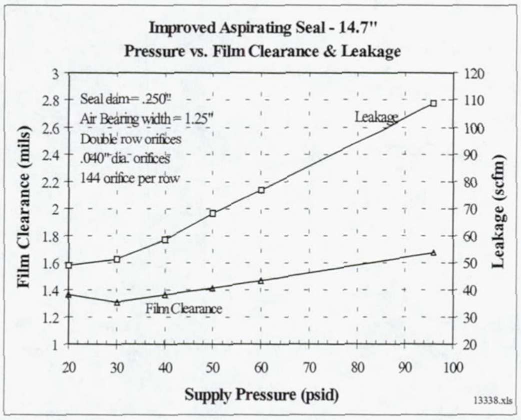
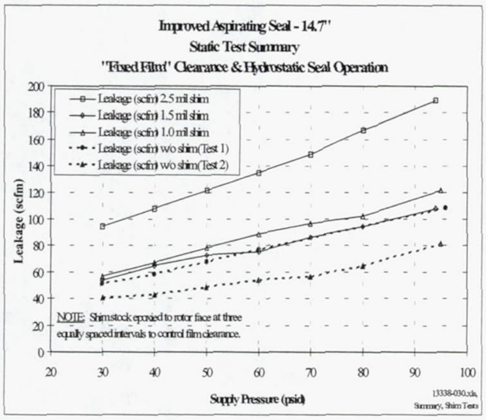
This photograph shows the seal instrumented with a proximity probe. The probe is mounted on a bracket that is attached to the OD of the seal. The probe is aimed at the rotor face in the dynamic test rig.

The view is looking at the sealing face.

Advanced Aspirating Seal

Static Test Results





Initial Test Results:

- Leakage ~ 1.15 scfm/psid
- Film gap = 1.6 mils @ 95 psid

Fixed Film Clearance Test Results:

- Clearance between Rotor & Seal Faces set with shim stock
- Prox probes measurements agree with shim calibration.

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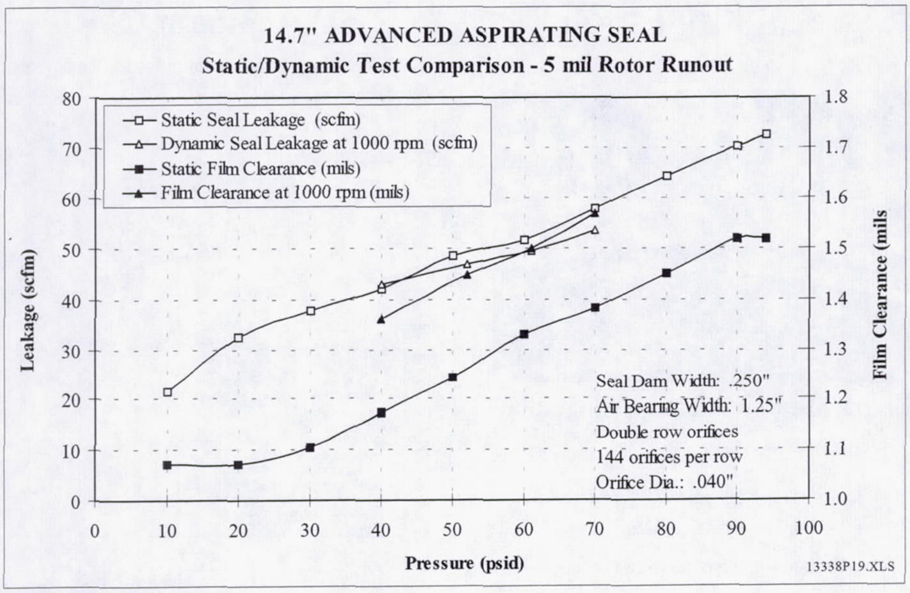
The two graphs represent seal performance on the dynamic test rig. Leakages include the primary face seal and the piston rig secondary seal.

Both graphs represent Pressure Differential vs. Seal leakage.

The graph on the left shows that the gas film clearance is approximately 1.6 mils at 95 psid.

The graph on the right shows the leakage for the “fixed film” clearance tests. The solid lines represent the “fixed film” performance, while the dotted lines represent the seal performance allowing the seal to float at its equilibrium point. In this graph, the film clearance is slightly less than 1 mil, running parallel to the 1 mil “fixed film“ clearance test curve.

Advanced Aspirating Seal



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This graph depicts the static and dynamic seal performance for Pressure vs. Leakage and Film clearance. The shaft speed for the dynamic test was 1,000 rpm (65 ft./sec.)

Leakage and film clearance are closely matched for static and dynamic test conditions.

The rotor face runout during the dynamic test was 5 mils.

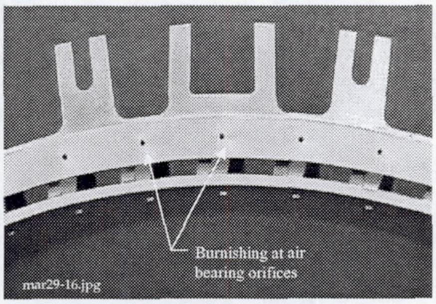
The results of the test demonstrate that the seal performance is very close to the analysis for film clearance measurements.

Test: 1.6 mils (static test @ 30 psid), 1.4 mils (dynamic @ 30 psid & 1,000 rpm)

Analysis: ~ 1.5 mils (30 psid)

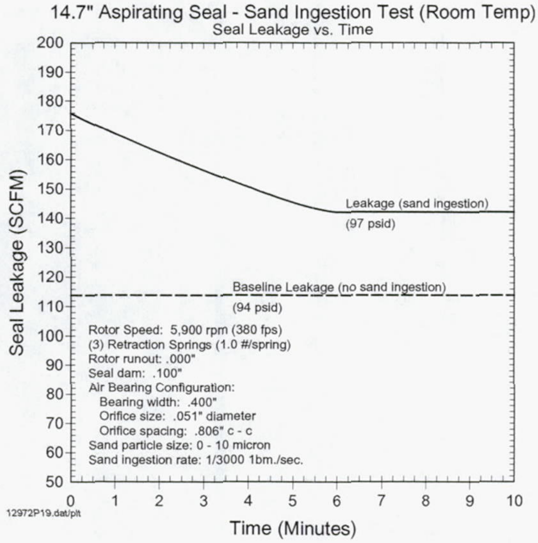
Advanced Aspirating Seal

Sand Ingestion Test - Original Aspirating Seal



Original Seal - "After Sand Ingestion"

- Sand delivered at:
  - 1/3000 lb./sec., 97 psid
  - 10 micron particle size
- No measurable damage to seal or rotor



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This slide is for reference. The sand ingestion was performed on the original seal with good results.

The sand was delivered into the test head for ten minutes at 1/3000 lbm/sec at 97 psid pressure differential.

The leakage at the onset of sand was approximately 54% higher than the leakage for a test without sand ingestion. As time passed, the leakage settled lower to approximately 24% higher than a seal without sand ingestion.

No damage was noted to the seal faces or orifice holes. It is noted that burnishing did occur near the orifice holes and on the rotor face. Slight burnishing appeared on the seal dam.

Advanced Aspirating Seal

Current Conclusions

- Seal operated successfully to:
  - 65 ft/sec (goal: 365 ft/sec)
  - 96 psid* (goal: 100 psid)
  - Room temp. (goal: 750 °F)
  - 5 mil Runout (goal: 10 mil)
- Seal performance is predictable
  - Stein analysis & validation tests agree
  - CFD analysis correlates computer codes & test data
  - NASA GFACE code correlates seal interface performance & provided additional information
- Tests are continuing

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Seal performance is predictable and validates the seal codes employed in the aspirating seal design. CFD is a valuable tool in the design of the aspirating seal to determine if the rotor flow diverrter is required. CFD correlated the Stein and NASA GFACE seal codes.

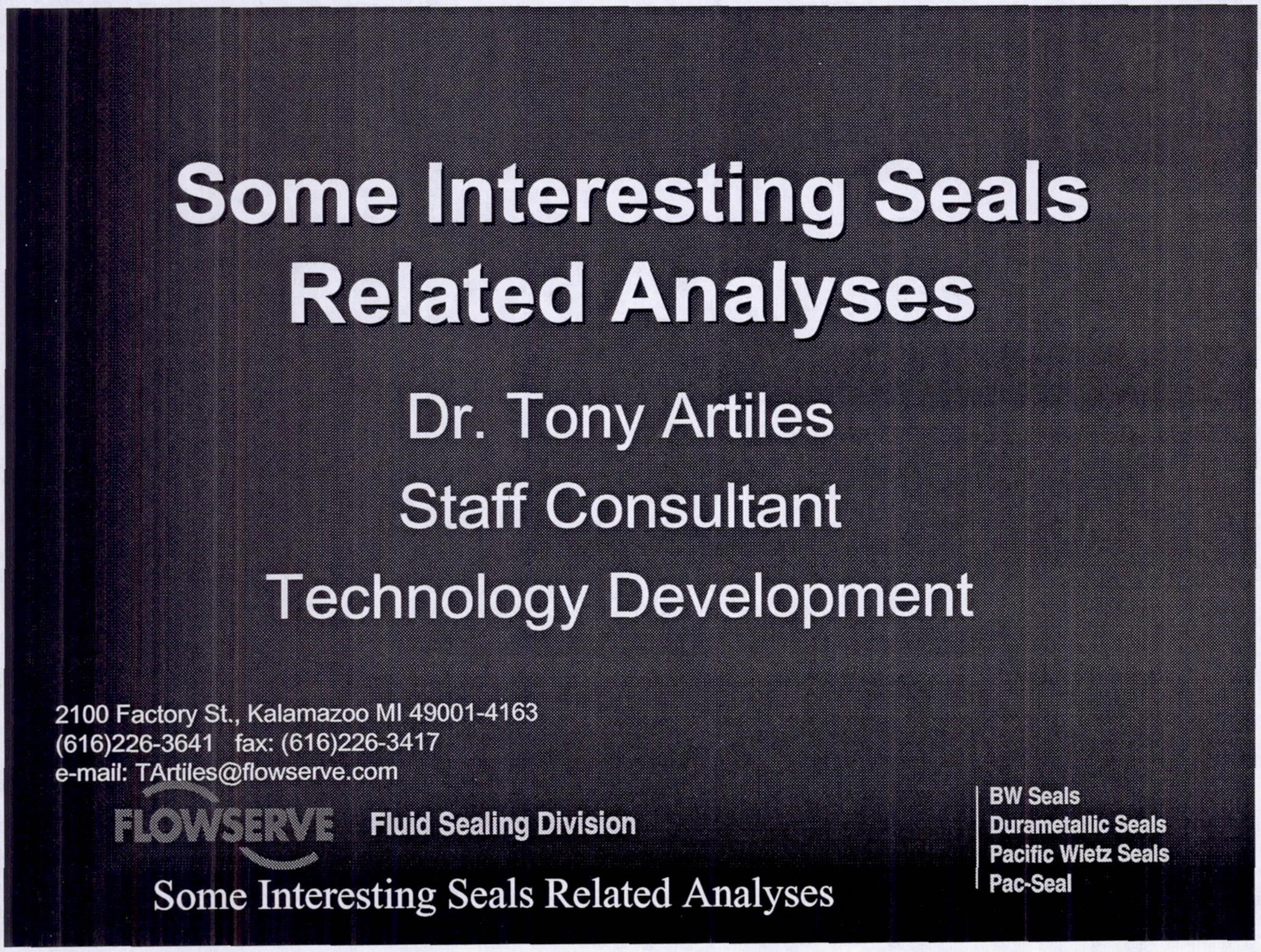
Further tests are required to fully prove the performance during all engine conditions.

The aspirating seal is an ideal alternative or replacement to brush seals operating in high pressure, high temperature conditions. The aspirating seal leakage is an order of magnitude less than the brush seal. The aspirating seal life can be infinite due to its non-contacting performance.

Rig tests are continuing are are necessary to further prove the success of the aspirating seal.

SOME INTERESTING SEALS RELATED ANALYSES

Tony Artiles
FlowServe
Kalamazoo, Michigan



Overview

Sample challenging analyses

- Demands on Mechanical Seals
- Pressure induced stator waviness
- Redesigning for a seal retainer a resonance away from excitation
- Ideas needed for STLE STC Advanced Projects Subcommittee

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Some Interesting Seals Related Analyses

BW Seals
Durametallic Seals
Pacific Wietz Seals
Pac-Seal

Exacting Demands on Mechanical Seal Surfaces

- Low leakage
- Low friction
- Low wear
- Low heat
- Low cost

- Remain close
- Remain **flat**
- Remain **steady**
- Remain parallel
- Not need replacement

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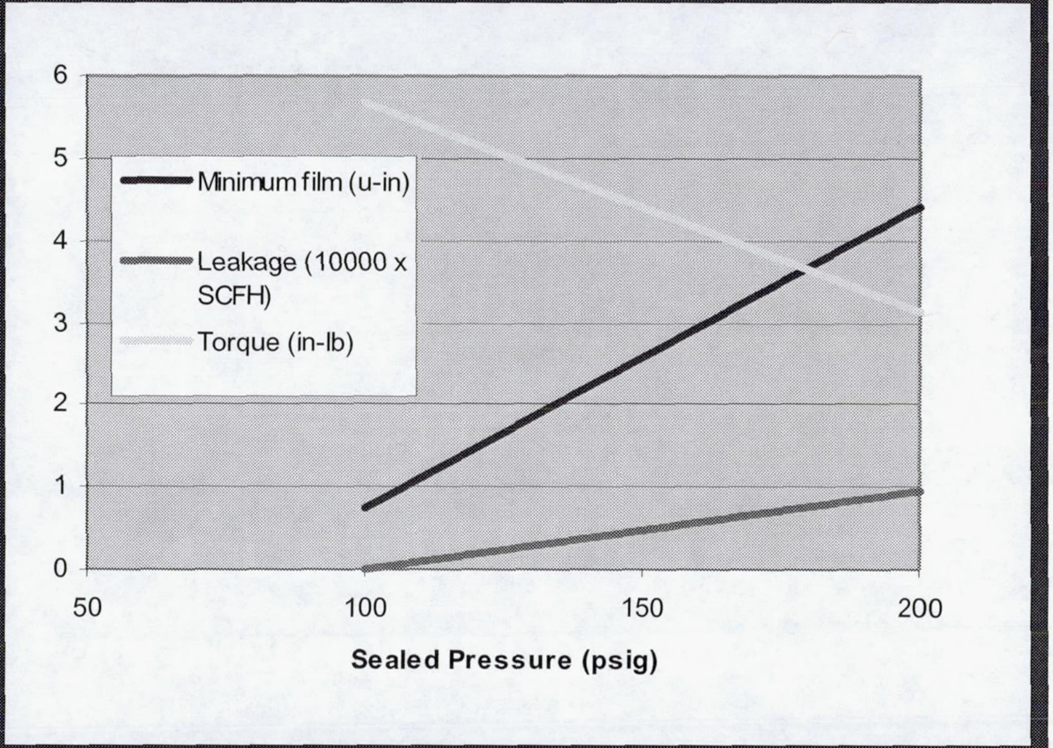
Pac-Seal

Some Interesting Seals Related Analyses

Hydrostatic liquid-lubricated pressure-balanced plain seal

Expected behavior with increasing pressure:

- Leakage increases
- Film thickness increases
- Torque decreases



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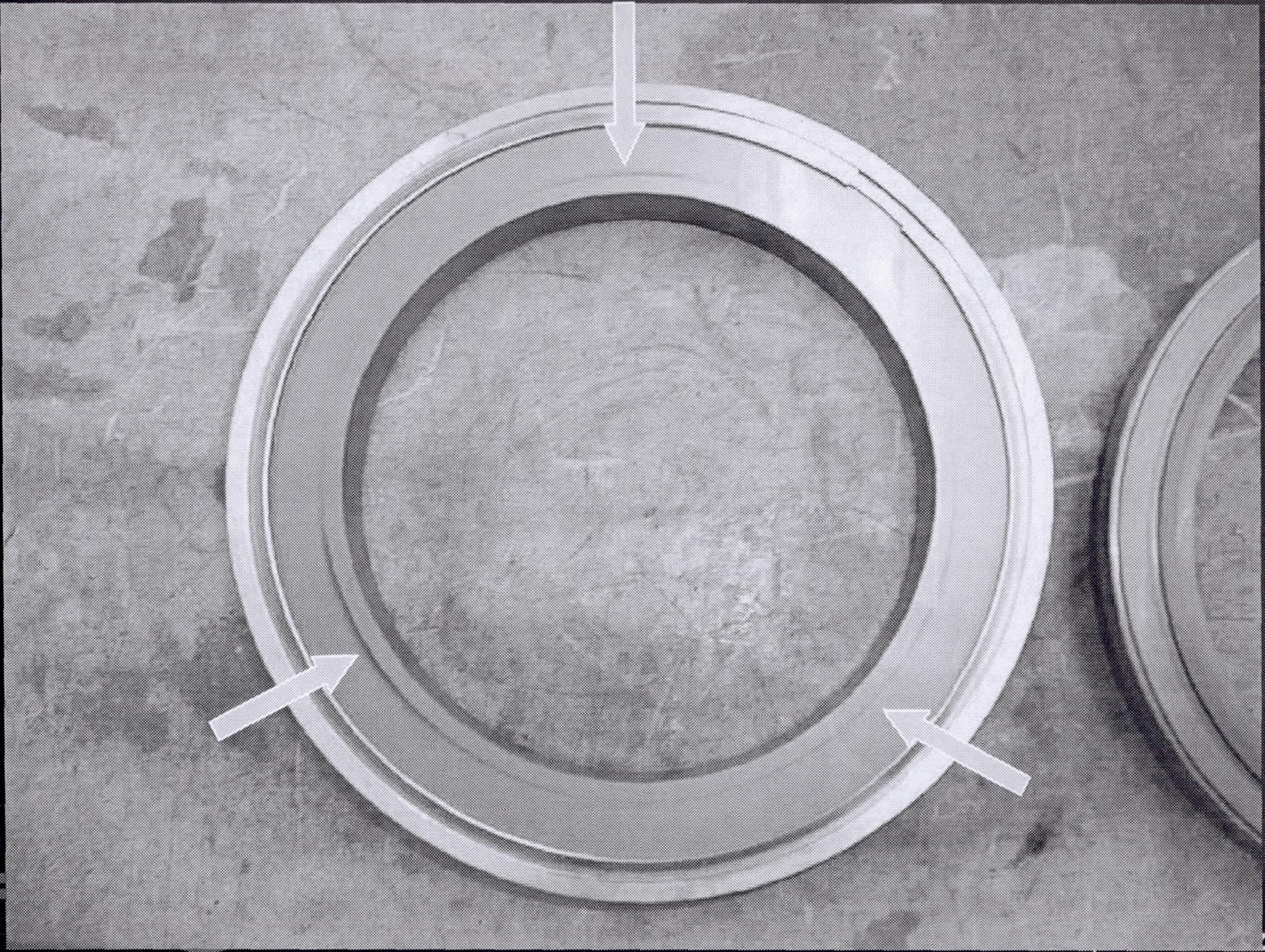
Pac-Seal

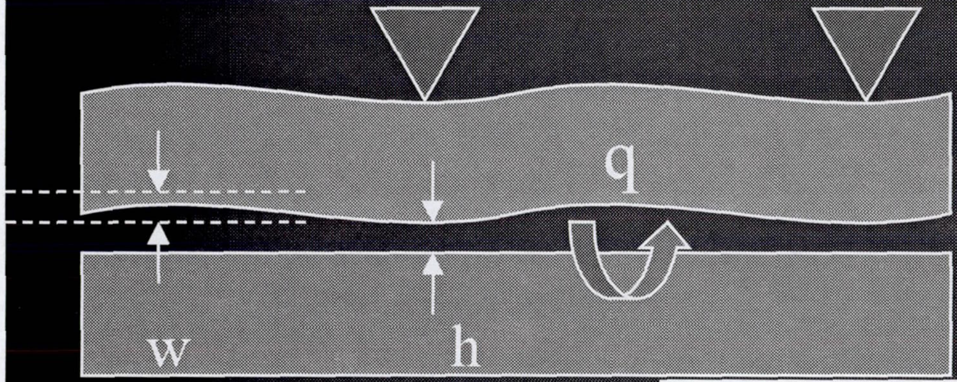
Pressure induced stator waviness



Seals
Seals
Pac-Seal

Some Interesting Seals Related Analyses

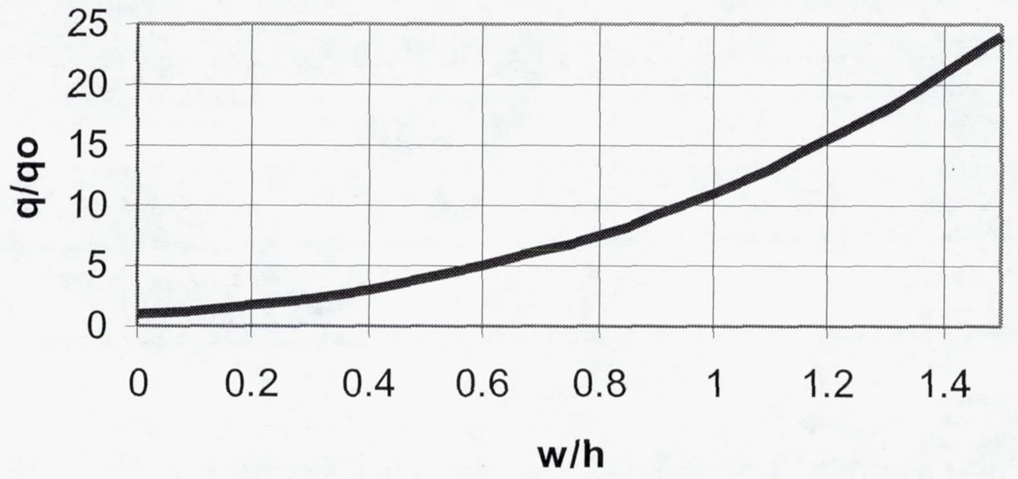
Waviness causes radial leakage



$$q := h^3 + 3\cdot h^2\cdot w + \frac{9}{2}\cdot h\cdot w^2 + \frac{5}{2}\cdot w^3$$

- But stator face was flat…
- 3-point support
- stator support surface flat?
- could pressure cause waviness?

Leakage factor versus waviness



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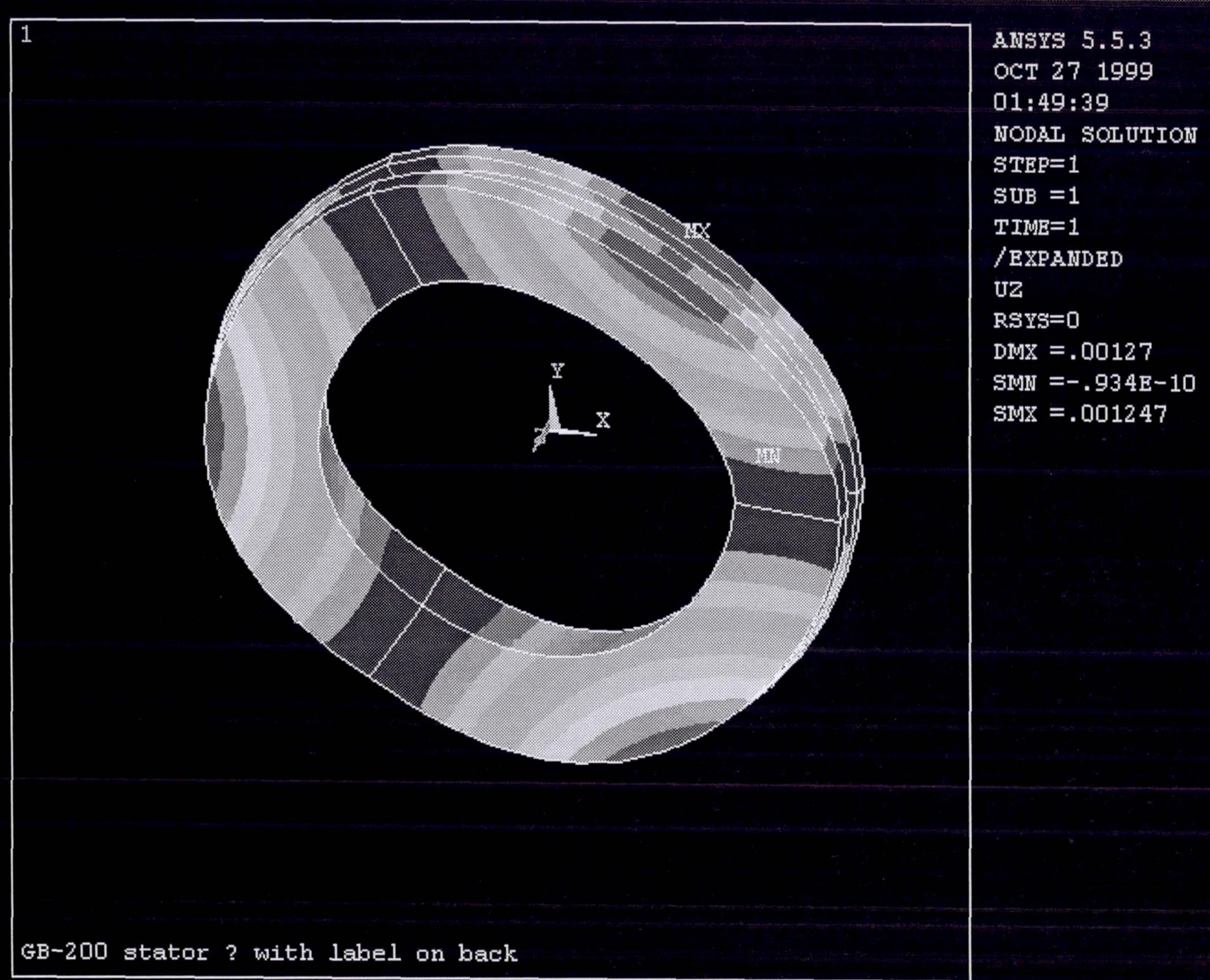
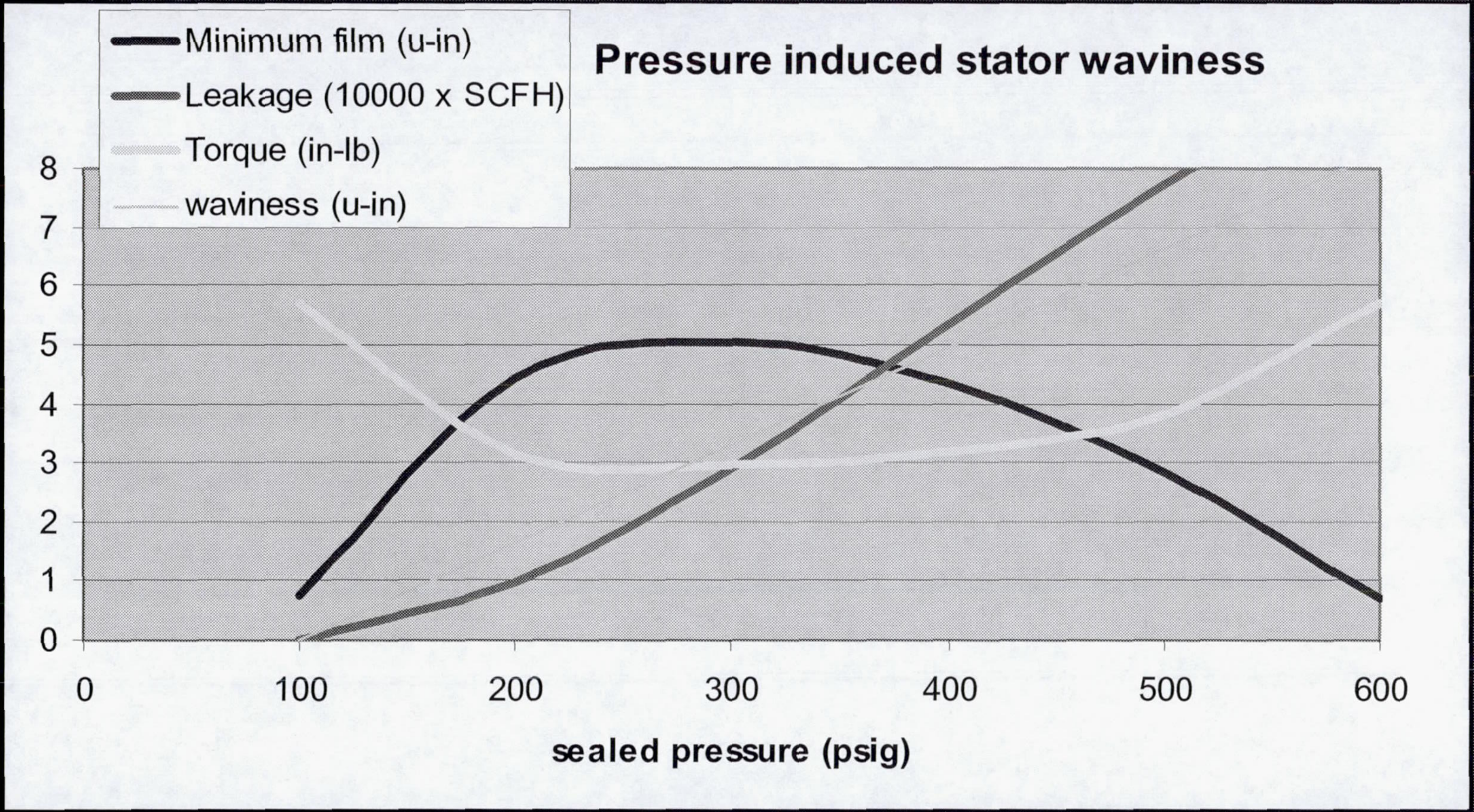
3-D model of ring loaded by pressure on 3 high spots on support



Seals
Seals

Pressure induced stator waviness



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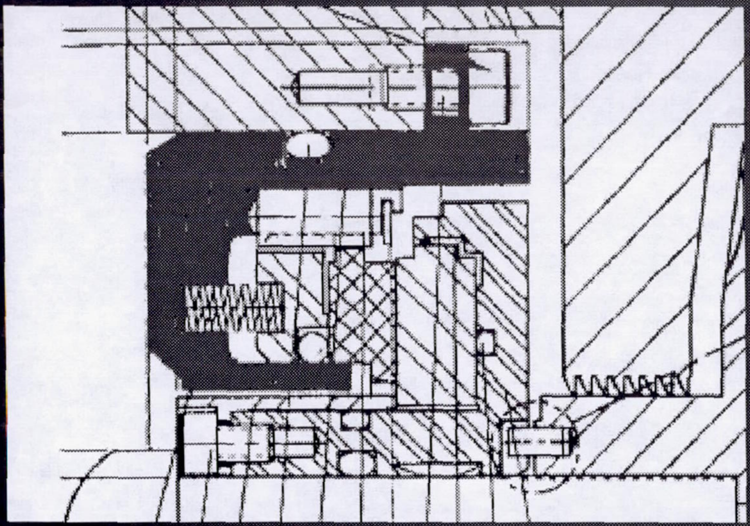
Some Interesting Seals Related Analyses

Seal holder resonance



Excitation frequencies	
Hz (14X)	Hz (15X)
5089	5452

measured	FEA Calculated	
Bench test	original design	% error
4,675	4,606	-1.5%
	4,700	0.5%
5,450	5,360	-1.7%
5,850	5,933	1.4%
6,275	6,283	0.1%
6,625	7,142	7.2%

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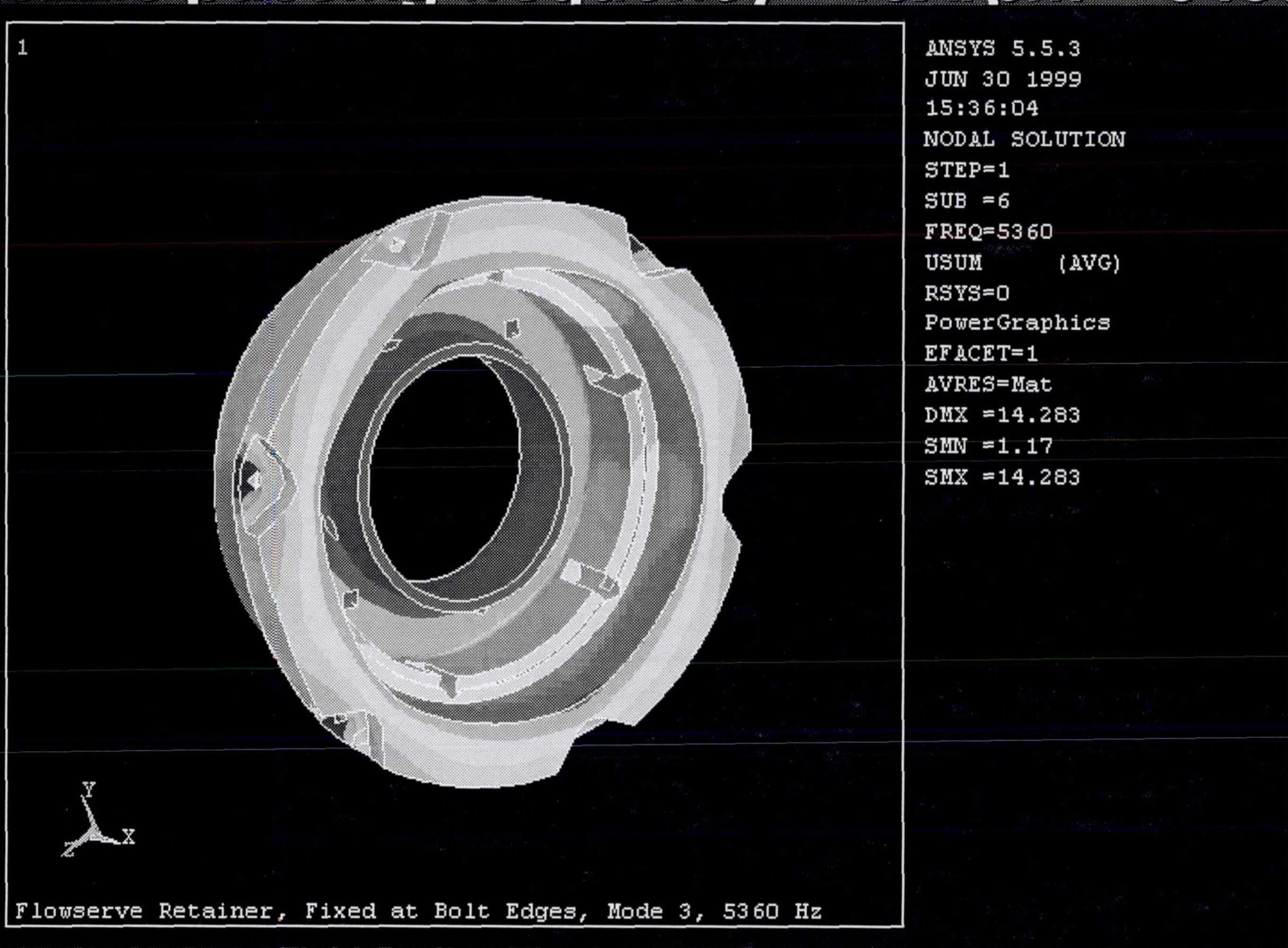
Some Interesting Seals Related Analyses

Resonance at 5360Hz
Nozzle passing frequency= 15Xrpm = 5450Hz



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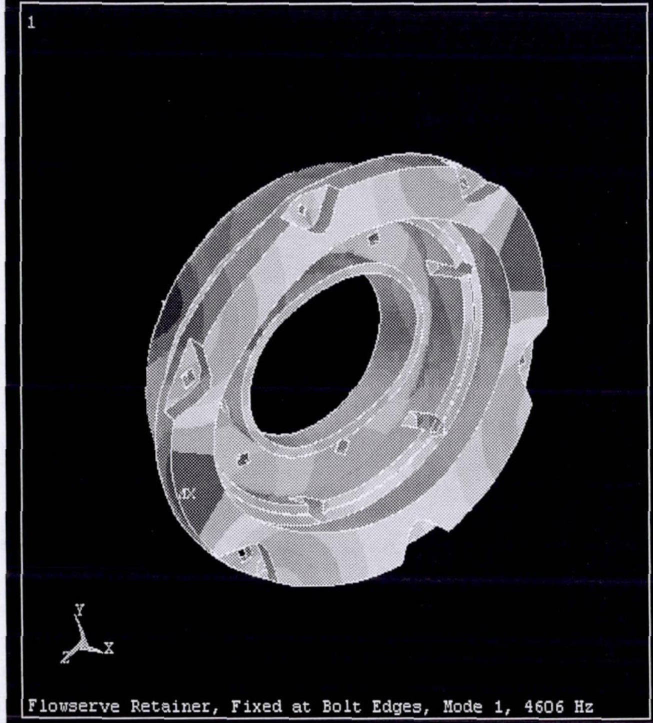
Some Interesting Seals Related Analyses

1st and 2nd natural frequencies



ANSYS 5.5.3
JUN 30 1999
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NODAL SOLUTION
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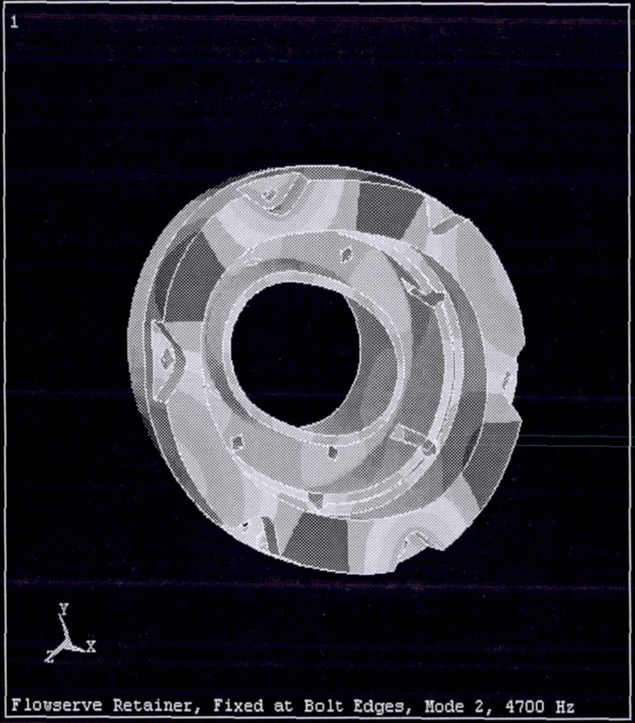
SUB =4
FREQ=4606
USUM (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
DMX =21.93
SMN =1.43
SMX =21.93



ANSYS 5.5.3
JUN 30 1999
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NODAL SOLUTION
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SUB =5
FREQ=4700
USUM (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
DMX =20.174
SMN =.752879
SMX =20.174

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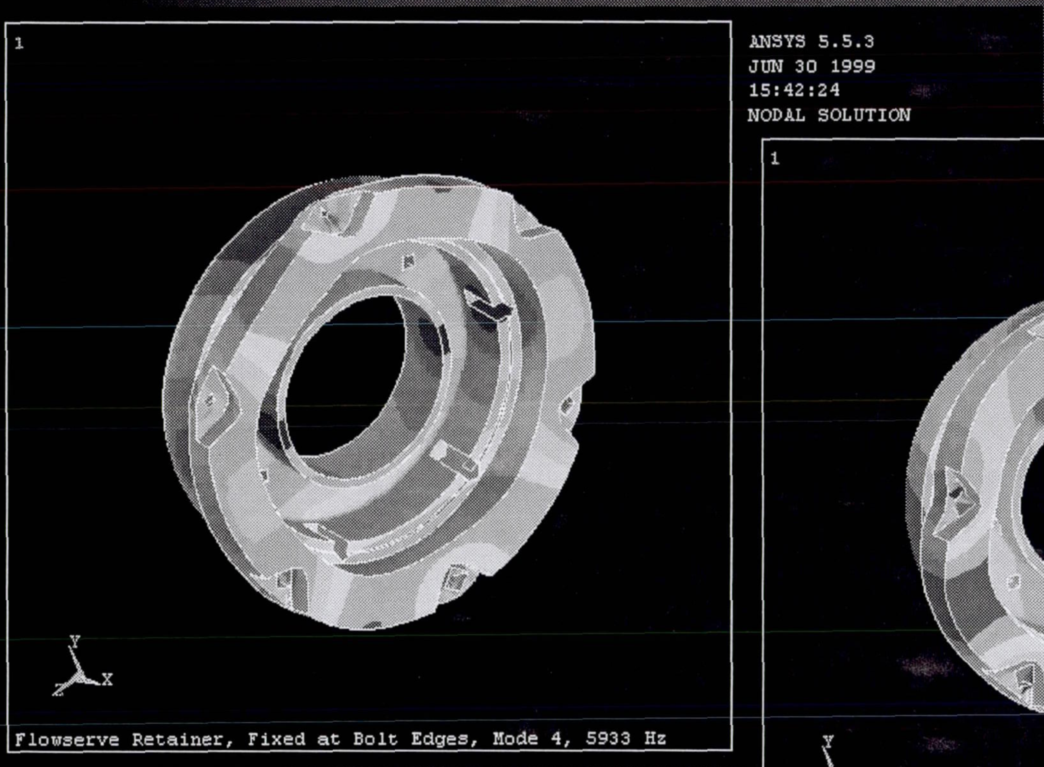
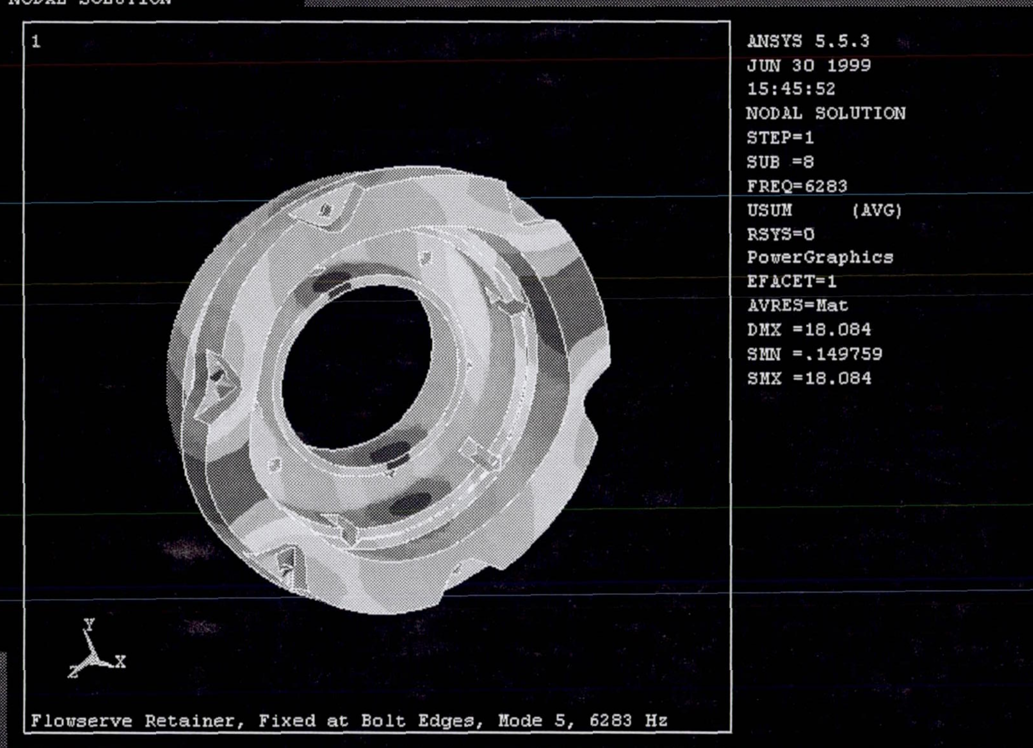
Pac-Seal

Some Interesting Seals Related Analyses

4th & 5th natural frequencies





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Duramettallic Seals
Pacific Wietz Seals
Pac-Seal

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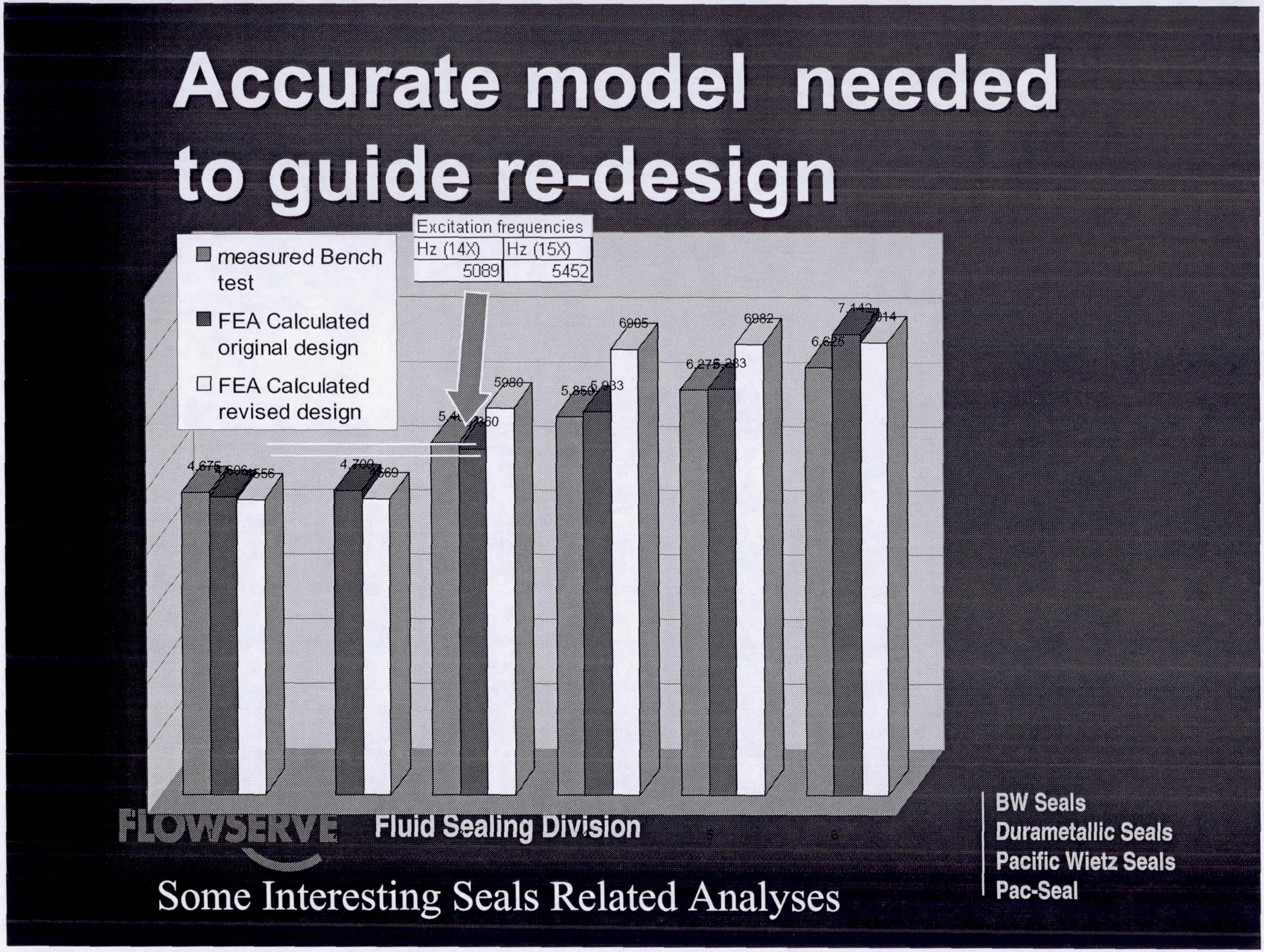
Accurate model needed to guide re-design
Excitation frequencies
Hz (14X)
Hz (15X)
5089
5452
measured Bench test
FEA Calculated original design
FEA Calculated revised design
4,675
4,556
4,700
4,569
5980
6905
6982
6,625
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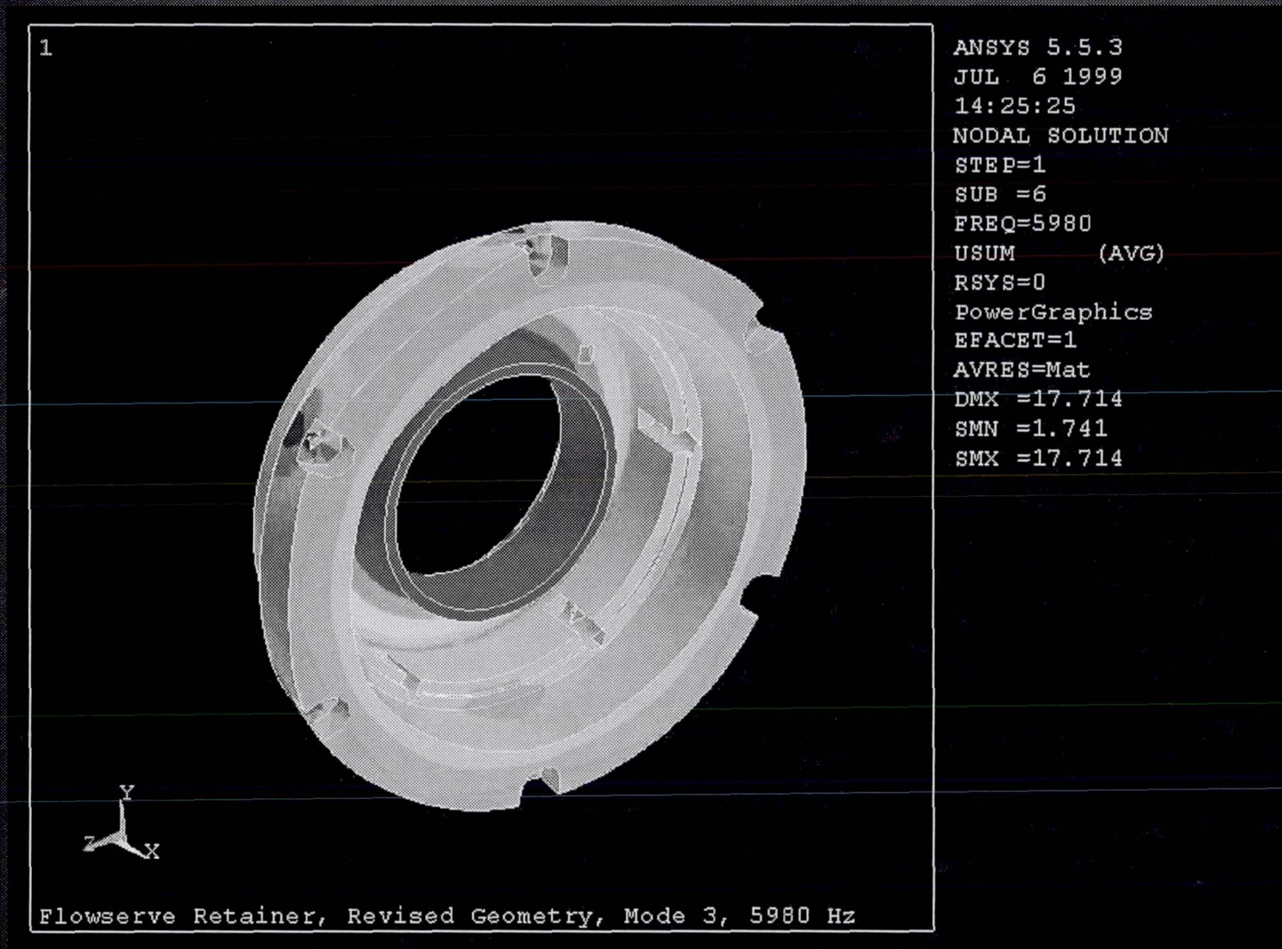
Pacific Wietz Seals
Pac-Seal

Redesign natural frequency= 10% higher



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Pac-Seal

Some Interesting Seals Related Analyses

Wrap Up

- Advanced analytical tools allows understanding accurate guide to challenging problems solutions
- Challenges ahead to educate engineers and designers, to use advanced tools to understand the behavior of machinery, aware of its limitations, to use as a guide in improving product performance.
- When qualitative analysis is sufficient, and when precise quantitative analysis is required
- STLE Advanced Projects Subcommittee needs input from end-users on research topics

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Some Interesting Seals Related Analyses

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Pac-Seal

HYDROSTATIC GAS SEAL PREDICTIONS

Wilbur Shapiro
WSA, Inc.
Niskayuna, New York

Glen Garrison
Stein Seal Company
Kulpsville, Pennsylvania

Hydrostatic Gas Seal Predictions

Wilbur Shapiro
WSA, Inc.
Glen Garrison
Stein Seal Company
NASA '99 Seals Workshop

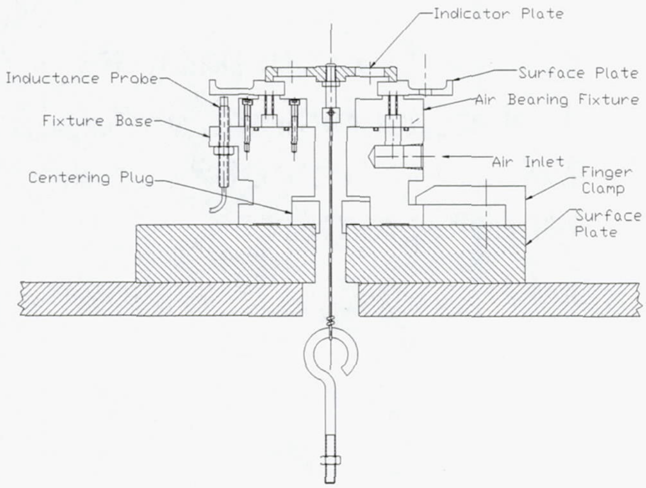
Data Bank

- Stein Seal Company has accumulated voluminous data on hydrostatic configurations
- Objectives were to compare theoretical predictions from code GFACE against test results

Test Rigs

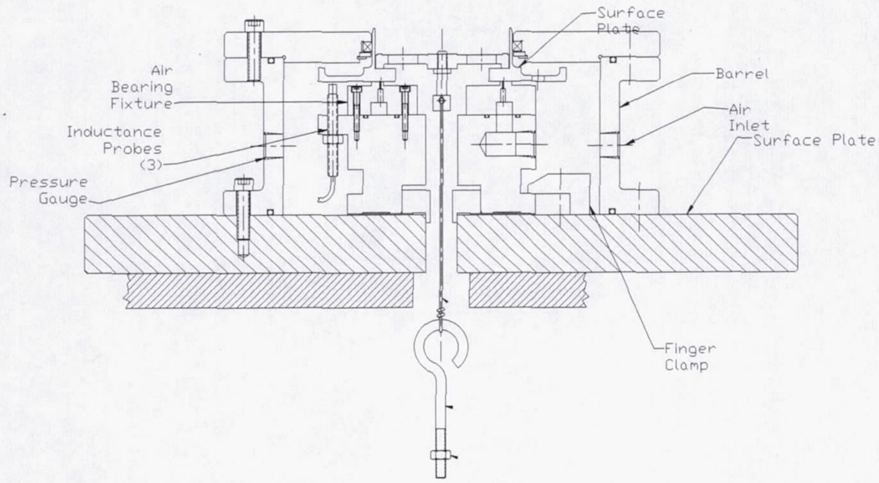
- Rigs with and without pressure barrel
- Principal measurements are clearance and leakage with constant applied load and variable pressure

Stein Static Test Rig



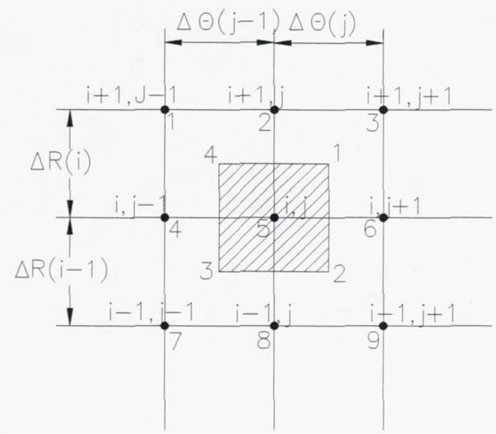
The air bearing fixture containing the hydrostatic configuration is mounted to a base plate. A surface plate loaded by dead weights is mounted atop the air bearing fixture. Pressurized inlet air to the base communicates with the fixture annulus to feed the hydrostatic orifices. Three inductance probes measure liftoff clearance and a flow meter measures inlet flow.

Static Test Rig –Pressurized Environment



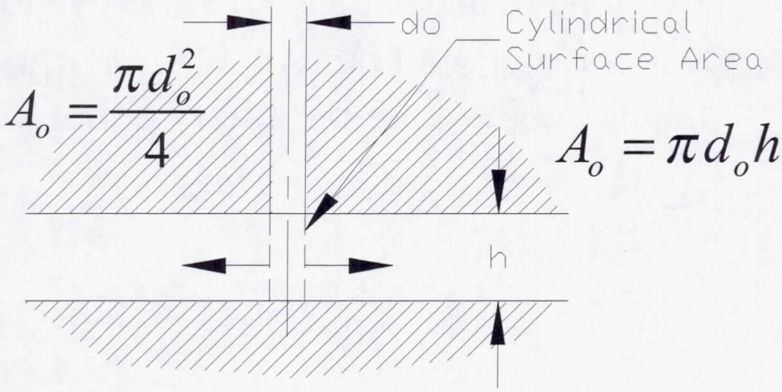
Often the hydrostatic seal is pressurized from the OD and the same pressure is used to feed the hydrostatic orifices. To simulate OD pressurization, a barrel is inserted around the fixture and the barrel is pressurized.

Grid Network



The analytical procedure models the interface with a grid network in the R-θ direction. A variable grid feature allows the spacing to vary in either direction. Surrounding each grid point a cell is inserted whose perimeter is bounded by half the distance to the adjacent grid point. The analytical procedure conducts a mass flow balance through the cell.

Source Point



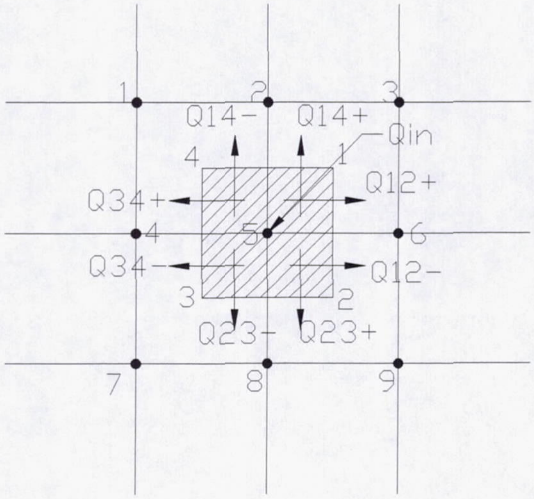
The variable grid identifies the locations of all the source points. At a source point the inlet flow traverses two orifices in series. The first orifice restriction is the hole itself and the second is the cylindrical surface area in the film. Note that the cylindrical surface area is clearance dependent. Generally, the cylindrical surface area is the major restriction.

Source Point

- Two orifices in series –hole and cylinder
- Cylinder modeled by variable grid and making rectangular periphery equal to

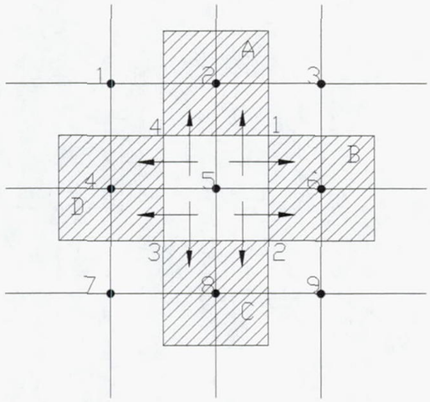
$$\pi d_o$$

Mass Flow Balance at Source



The solution process requires a mass balance at each grid point. At a source point the balance includes inlet flow from the hole and outflow around the periphery. The periphery is made equal to the circumference of the cylinder by implementing the variable grid properties of the code. The flow into and out of the source cell utilizes the orifice equations.

Cell Neighbors



The code incorporate provisions to assure that flow into the cells surrounding the source point equals the corresponding outflow from the source cell.

Flow Equations

- Laminar

$$Q = -\frac{PH^3}{R}\frac{\partial P}{\partial \theta}\frac{\Delta R}{2} + \Lambda RPH\frac{\Delta R}{2}$$

- Orifice

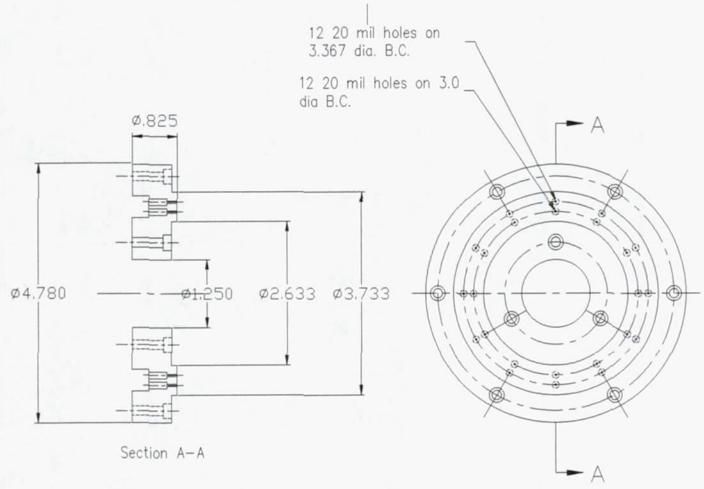
$$Q = (OFC)(A_o)P_s\left\{\left(\frac{P_r}{P_s}\right)^{\frac{2}{\gamma}}\left[1-\left(\frac{P_r}{P_s}\right)^{\frac{\gamma-1}{\gamma}}\right]\right\}^{\frac{1}{2}}$$

$$if\ \frac{P_r}{P_s} \le P_{cr}\ then\ \frac{P_r}{P_s} = P_{cr}$$

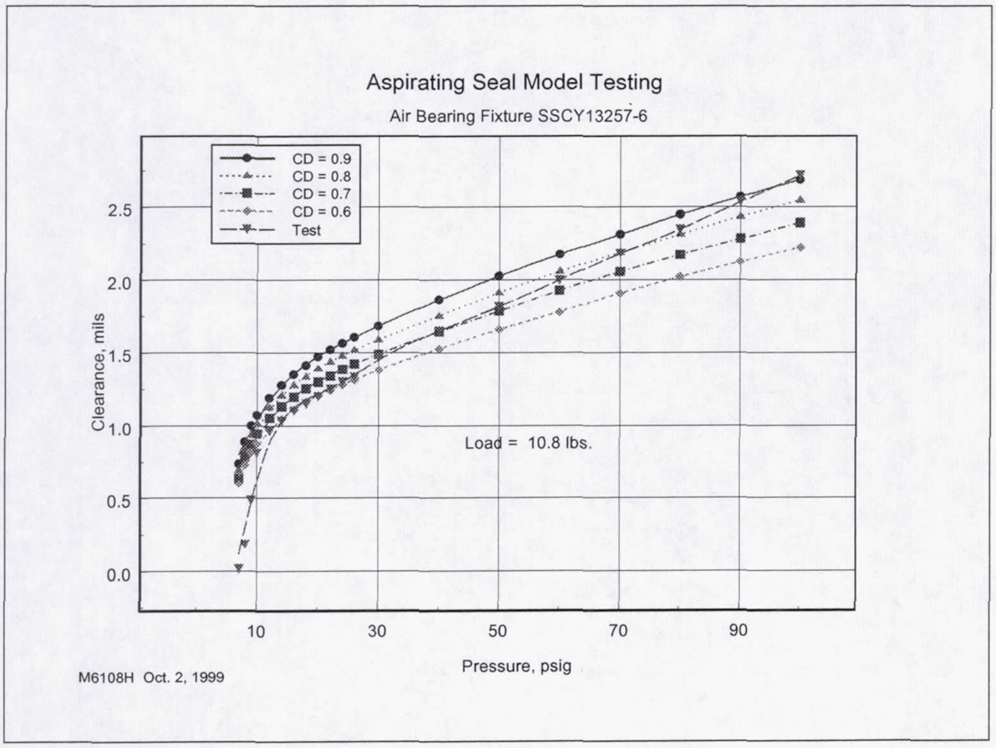
$$where\ P_{cr} = \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}$$

The principal flow equation throughout the grid is the laminar flow equations emanating from the Reynolds equation. Exceptions at at source points and inertia lines where the orifice equations are applied.

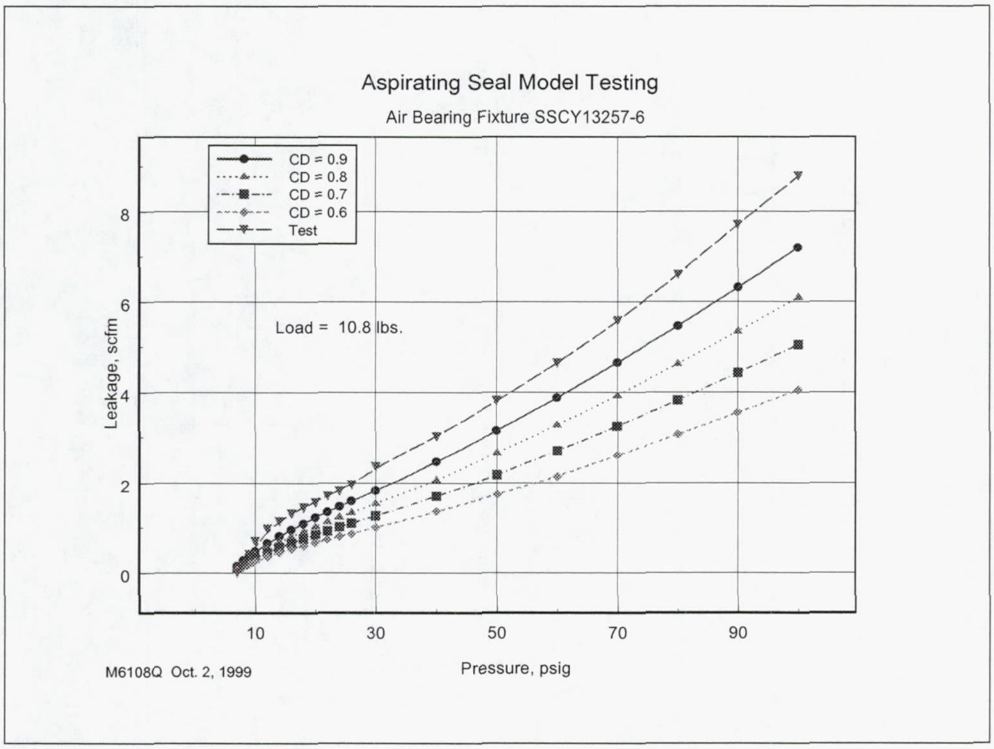
Hydrostatic Configuration



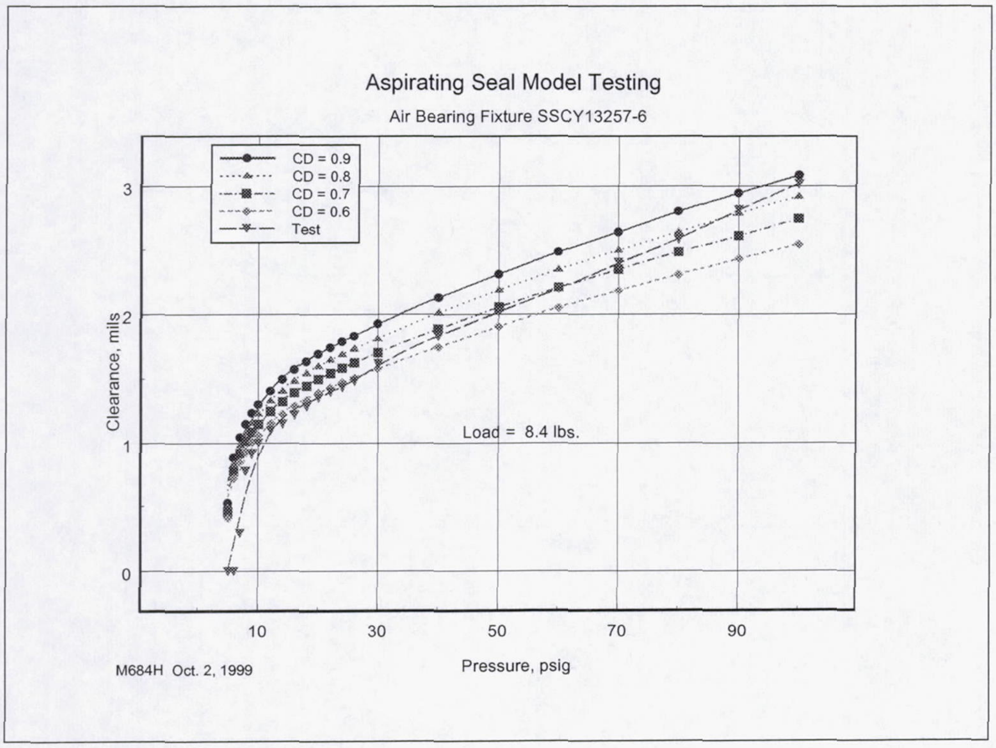
One of the configurations tested and analyzed is shown on slide12. It consists of a double row of aligned orifices. Each row has 12 holes of 20 mil diameter. One row is on a 3.367 B.C. and the other on a 3.0 inch B.C. The OD of the hydrostatic interface is 3.733 in and the ID is 2.633 in.



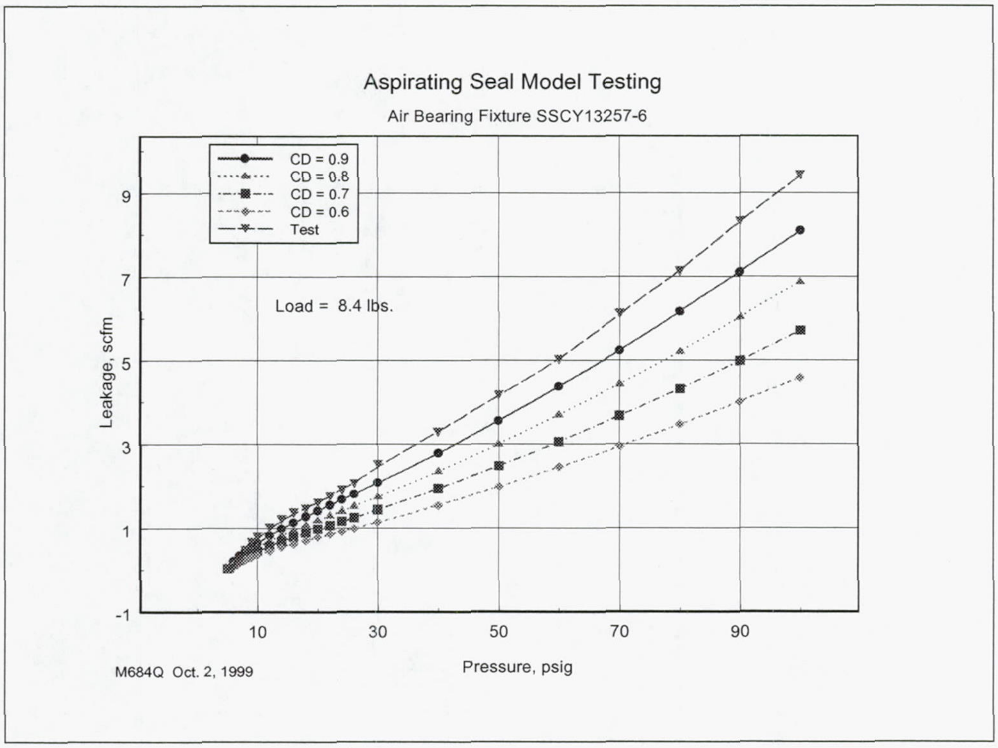
A load of 10.8 lbs was applied to the test rig with the hydrostatic configuration of slide 12 in place. The test procedure was to vary the supply pressure and measure clearance and leakage. Test results are indicated by the inverted solid triangle. Superimposed are theoretical results with variations in the Coefficient of Discharge.



Flow results are indicated on this slide. Note that the test results indicate slightly higher values than the theoretical results which was consistent for all applied loads.



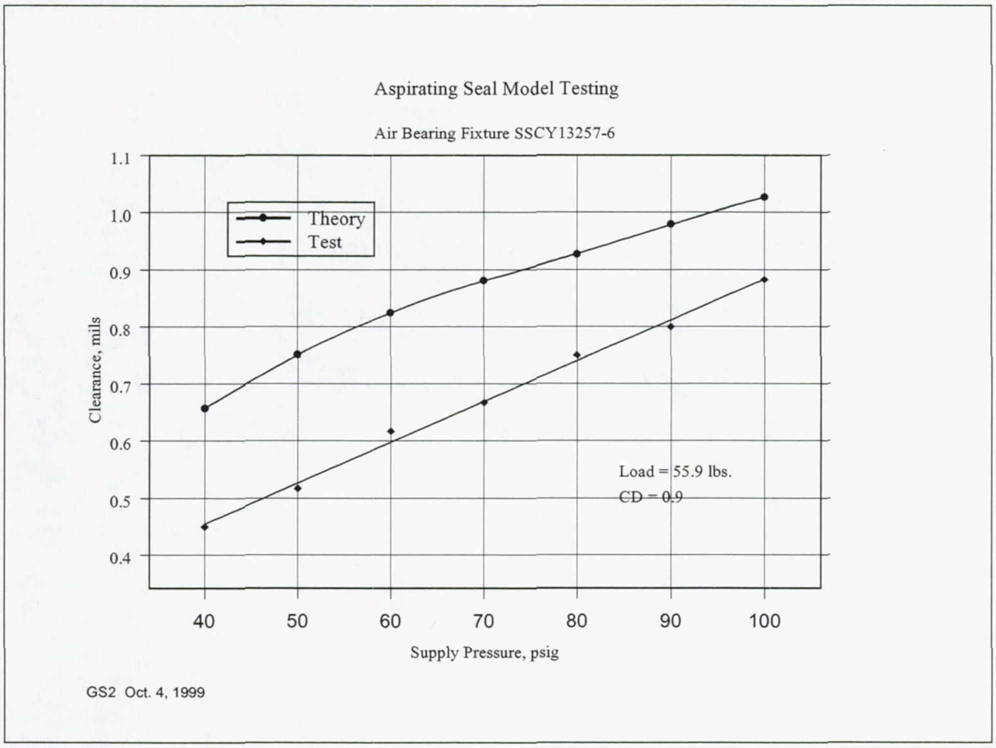
Similar results are indicated for a different applied load. Note that a Cd of 0.9 produces slightly higher clearances. However leakage results for Cd of 0.9 show slightly lower values.



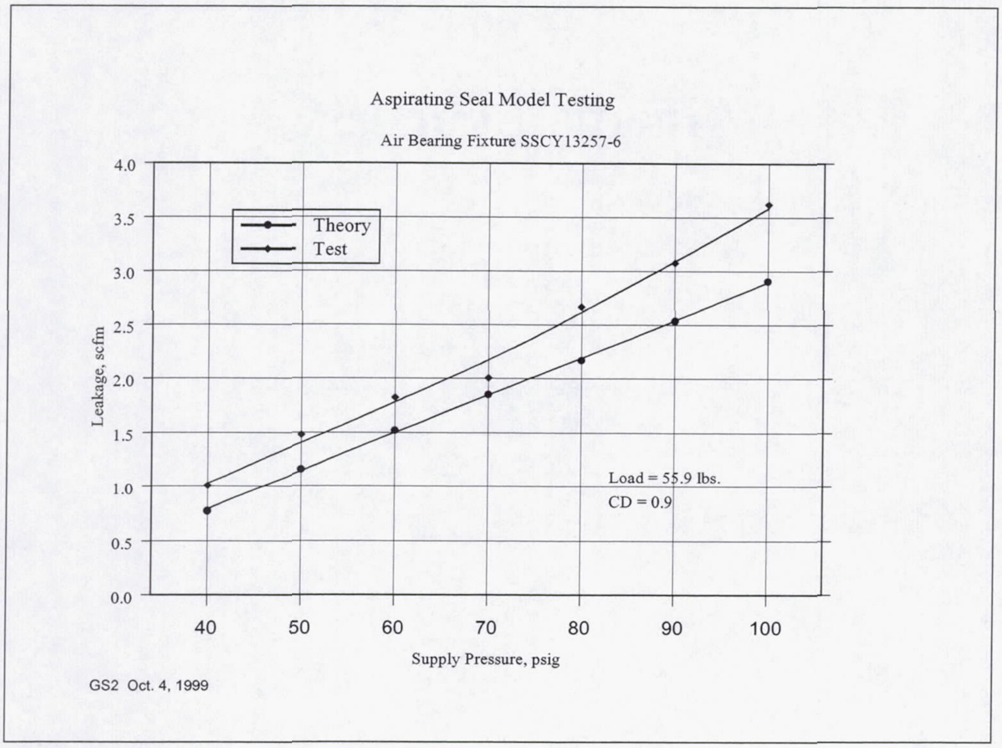
Leakage results at a Cd of 0.9 are slightly lower than test results.

Conclusions

- Theoretical leakage is lower
- Best compromise is Cd = 0.9
- Provides slightly higher clearance and slightly lower leakage

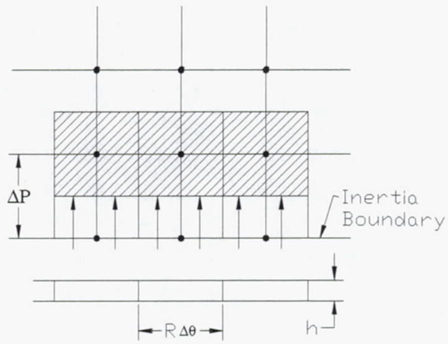


Results for a Cd of 0.9 at a high load are indicated on this Figure.



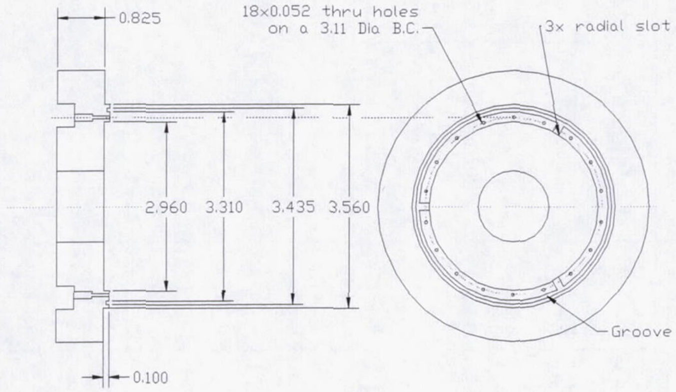
Leakage results are indicated here.

Inertia Boundary

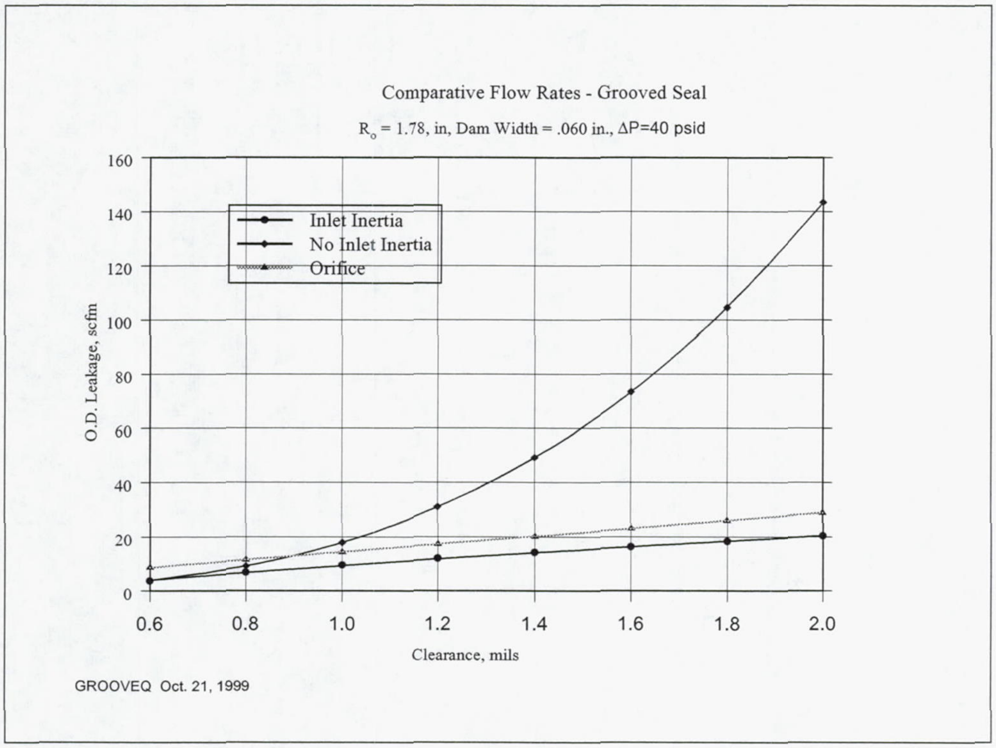


At an inertia boundary The flow into the interior cell is evaluated two ways. The first uses the conventional laminar equations and the second employs the orifice equation. The least of the two flows is selected since it represents the major restriction. Inertia boundaries are important as the clearance grows because laminar flow theory is proportional to the cube of the clearance and result in grossly exaggerated flows.

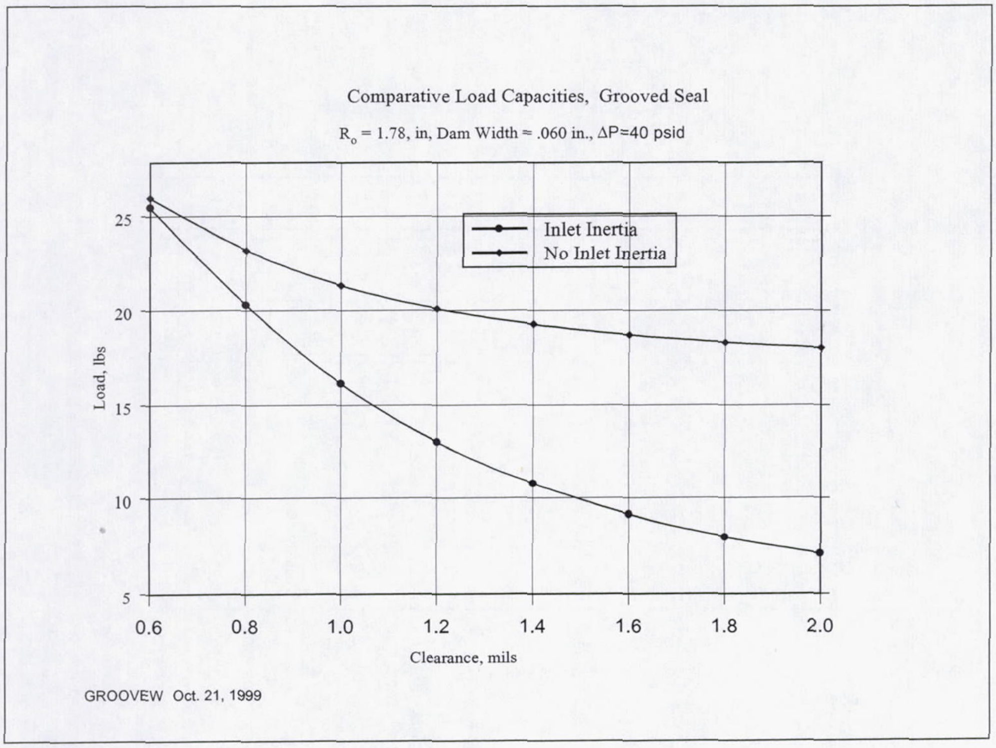
Seal Configuration with Boundary Pressure



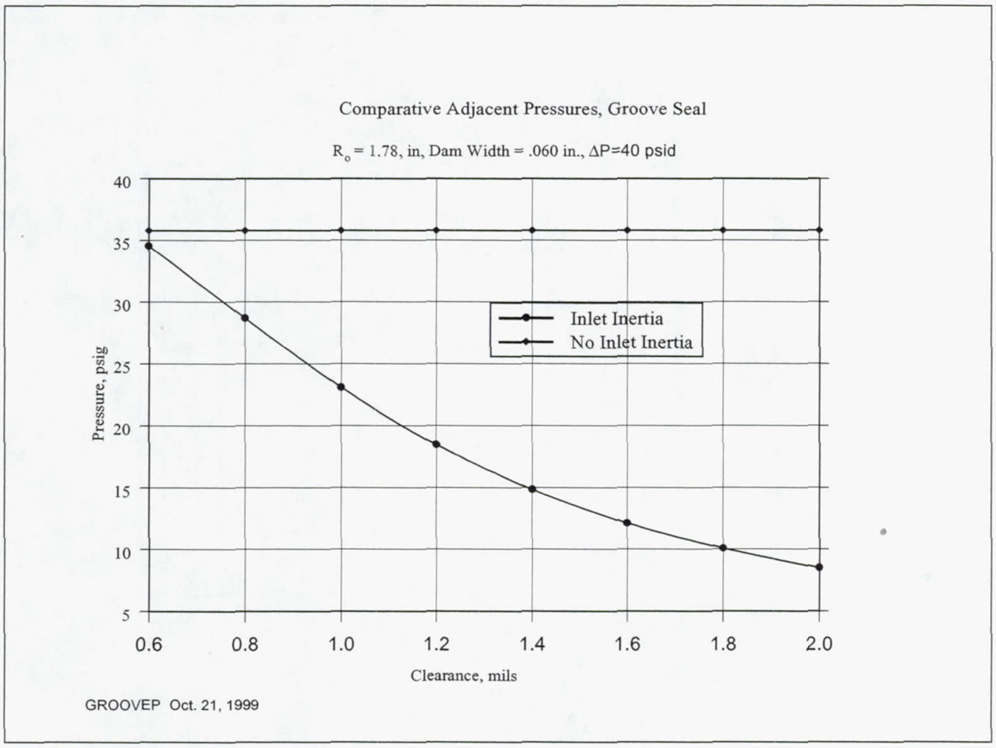
This slide indicates another configuration that will shortly undergo static testing. A deep groove is machined in the hydrostatic interface that communicates with radial slots that exhaust to the ID. High pressure is applied at the OD and also feeds the orifices. The ID is at ambient pressure of 14.7 psia. The groove pressure equals ambient because of the radial slot communication. The concept was designed to surround the hydrostatic region with ambient pressure to improve hydrostatic stiffness and righting moment capacity. The seal dam, which is the region above the groove, is quite narrow as is the entire interface. The leakage across the dam must include inertia effects because of the small aspect ratio.



Theoretical leakage across the seal dam, of the previous configuration, as a function of clearance is shown on this slide. Laminar theory applies to the upper curve. For low clearances of 0.8 to 0.9 mils, laminar theory provides the major restriction because it is lower than the inertia flow and would govern. For subsequent clearance increase, inertia or orifice flow governs as indicated by the lower curve. Note the significant difference in flow between the two theories. Also indicated on the plot is flow as a sharp edged orifice with a full pressure drop of 40 psid. This curve is the choked flow condition and represents the maximum flow that could occur across the seal land for a constant clearance condition.



It is important to accurately establish the opening load capacity of the seal so a proper balance ratio can be designed. There is a significant reduction in load capacity between laminar and inertia theory at the higher clearances. This occurs because of the immediate pressure reduction of inertia theory as indicated on the following slide.



With inlet inertia applied there is a significant pressure reduction immediately adjacent to the boundary which effects all subsequent downstream pressures and results in reduced load capacity. For laminar theory there is hardly any change in the immediate downstream pressure as the clearance increases. Primary pressure reductions occur further downstream.

Conclusions

- GFACE modifications include series orifices at source point and inlet inertia effects.
- Modified code predicts performance of hydrostatic seal reasonably well
- Inlet inertia important for low aspect ratio seals

Conclusions (cont'd)

- Low aspect ratio hydrostatic seals with OD pressure can be prone to moment unbalance instability

Some problems have been experienced with low aspect ratio hydrostatic seals. Righting moments can be insufficient to prevent overturning of the seal. Moment unbalance instability can be of serious consequence in low aspect ratio film seals. Inclined film distributions can result in excessive flow, increased load capacity, and possible contact.

ADVANCED SEALS FOR GENERAL AVIATION ENGINES

Mohsen Salehi and Hooshang Heshmat
Mohawk Innovative Technology, Inc.
Albany, New York

Mohawk Innovative Technology, Inc.

Advanced Seals for General Aviation Engines

Mohawk Innovative Technology, Inc.

NASA Seal Workshop
NASA/GRC
October 1999

Mohsen Salehi, Ph.D.
Hooshang Heshmat*, Ph.D.
* STLE, ASME Fellow

Mohawk Innovative Technology Inc.,
1037 Watervliet-Shaker Rd.
Albany, NY 12205
miti@albany.net
www.mohawkinnovative.com

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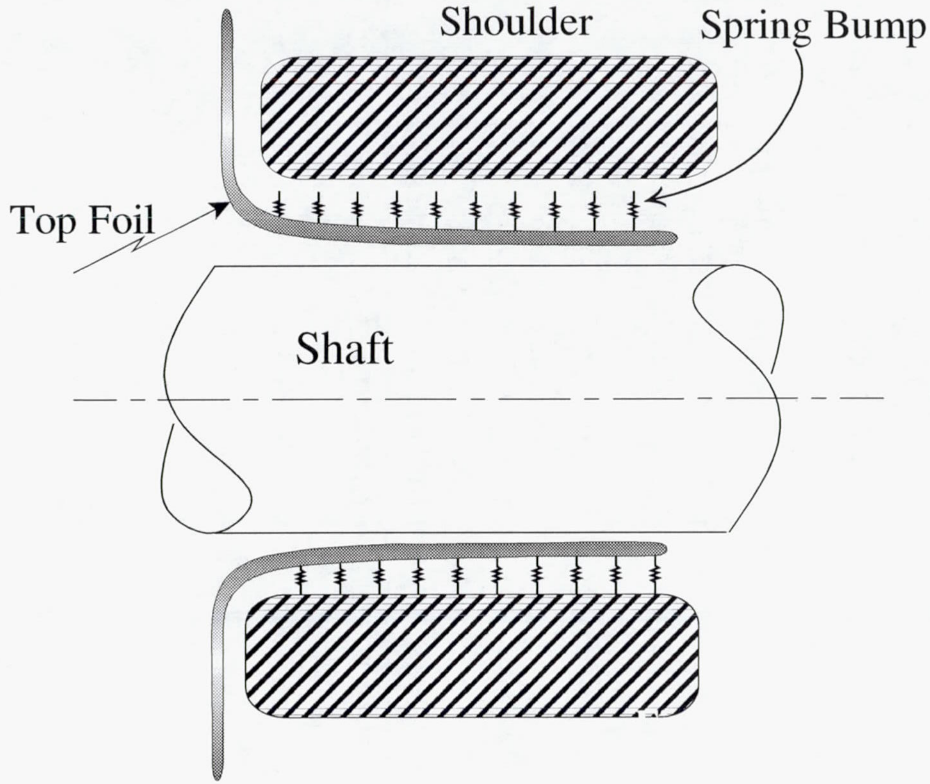
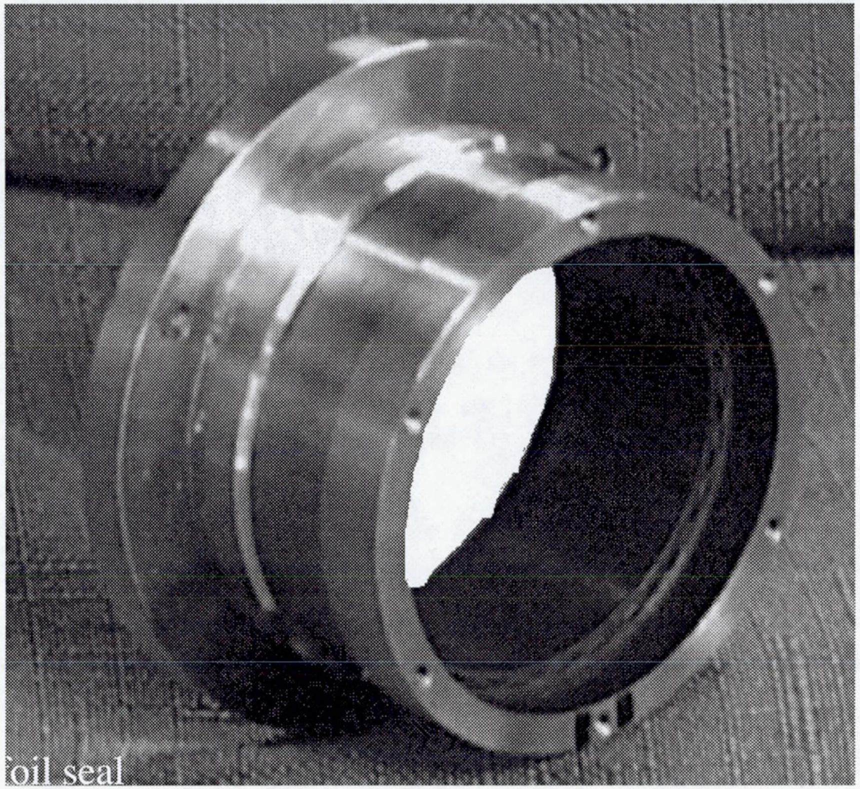
Compliant Foil Seal - Physical Model/prototype





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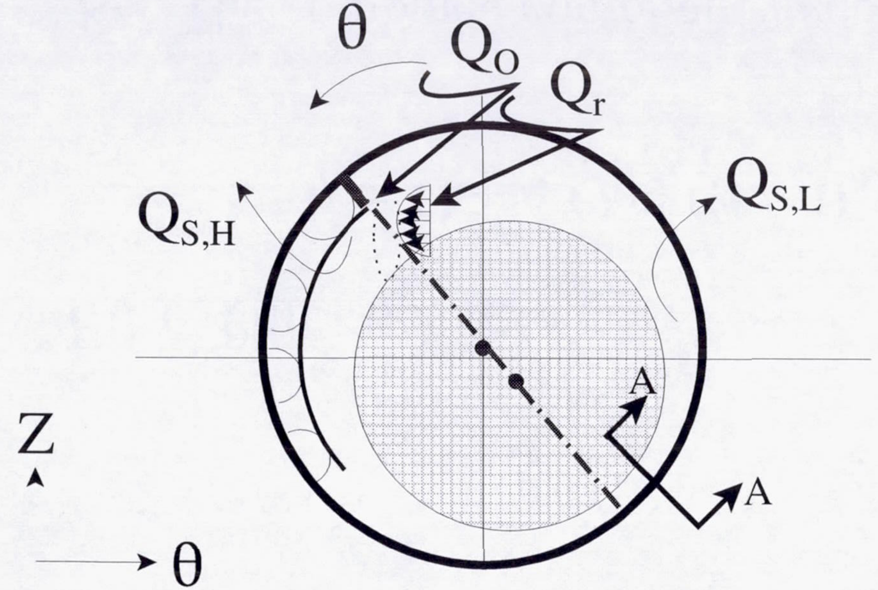
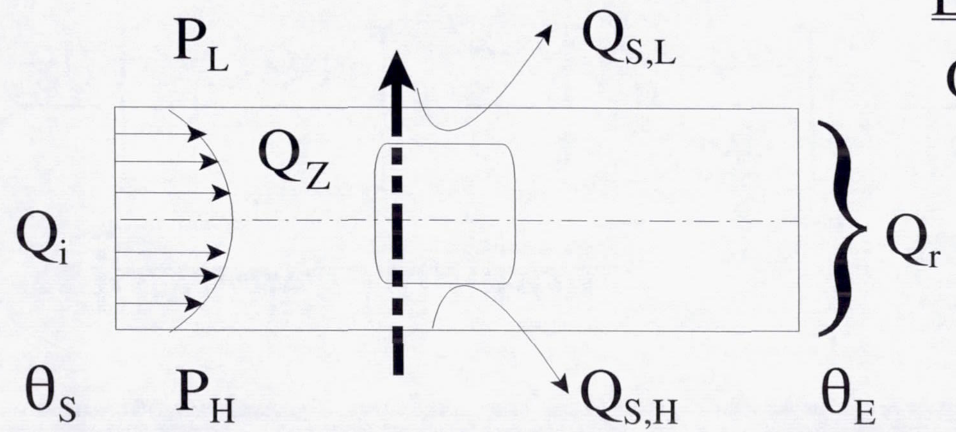
98-0268

A Simplified Flow Model & Thermal Effects in a Foil Seal





Side Flow

$$Q_S \approx Q_{S,L} + Q_{S,H}$$

$$Q_i \approx Q_r$$

Inlet

$$Q_i \approx Q_O + Q_r$$

$$T_i = f\,(T_O, T_r)$$

Energy Balance Approximation

$$Q_i\,T_i + H_{gen} \approx Q_S T_{S,avg} + Q_r\,T_{max,avg}$$

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Governing Equations and Boundary Conditions

Reynolds Equation:

Velocity & Inertia

$$\frac{\partial}{\partial\theta}\left[\bar{P}\,\bar{h}^{3}\,\frac{\partial\bar{p}}{\partial\theta}\right] + \frac{\partial}{\partial\bar{z}}\left[\bar{P}\,\bar{h}^{3}\,\frac{\partial\bar{p}}{\partial z}\right] = \Lambda\,\frac{\partial}{\partial\theta}\,(\bar{P}\,\bar{h})$$

$\bar{z} = (Z/R)$ $\bar{p} = (P/P_L)$ $\bar{h} = (h/C)$

Film Thickness :

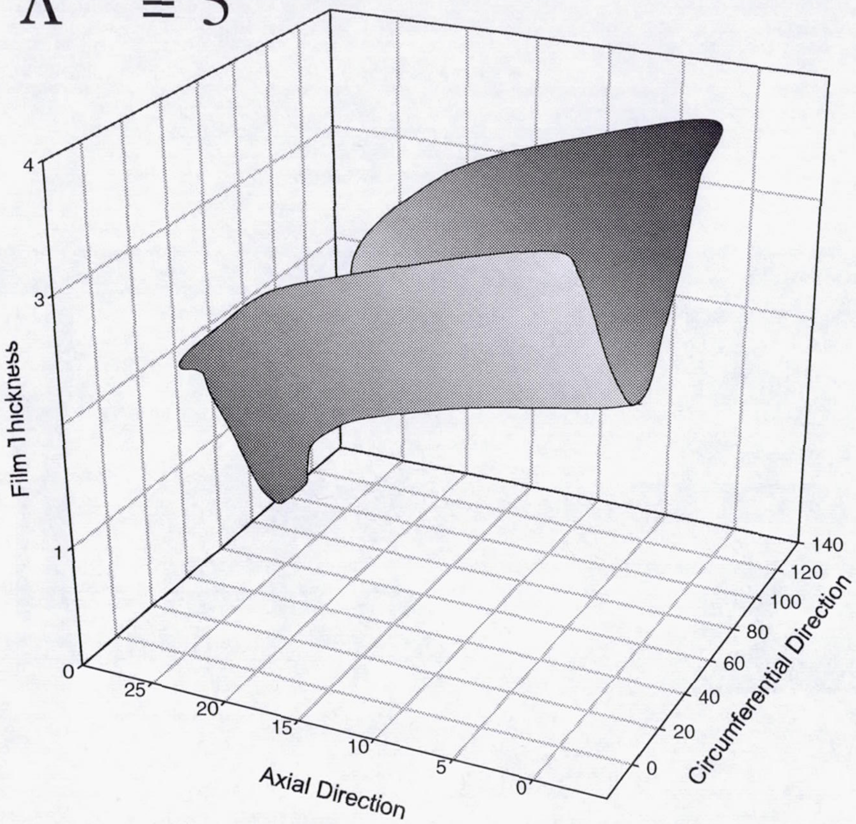
$$\mathbf{h = C + e\,Cos\,(\theta - \theta_0) + \overbrace{\sum K_{ij}\,(p_{eff} - P_N)}^{\text{Compliancy}}}$$

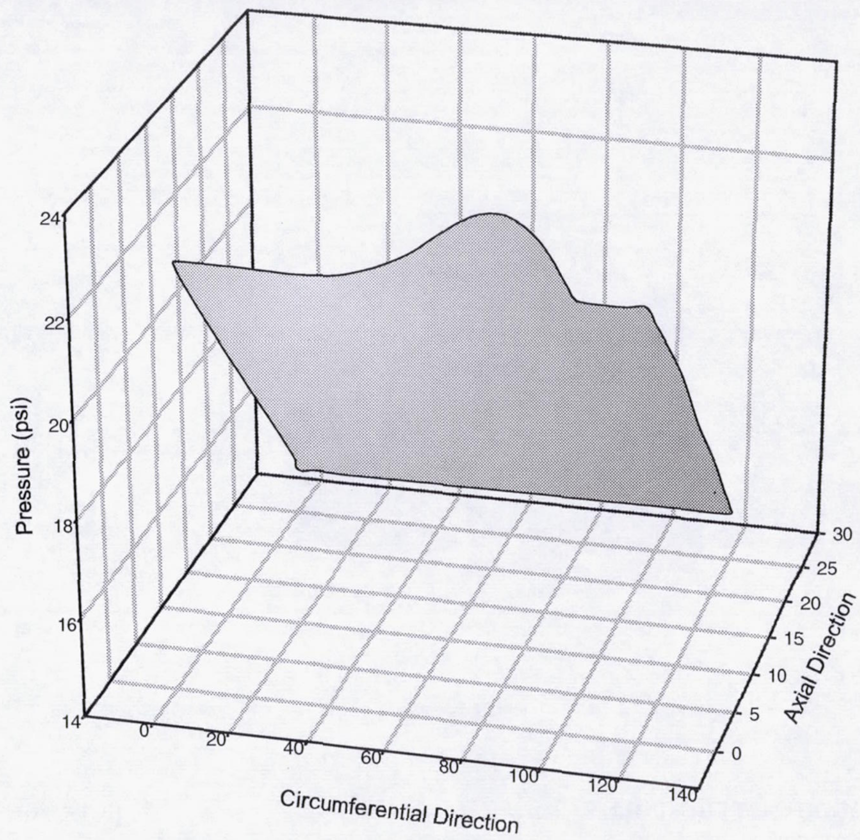
K_{ij} : The combined compliancy coefficeint

P_N: Normalized pressure behind foils

Film Thickness and Pressure Distribution

L/D = 0.5
ΔP = 7.5 psi
Λ = 5





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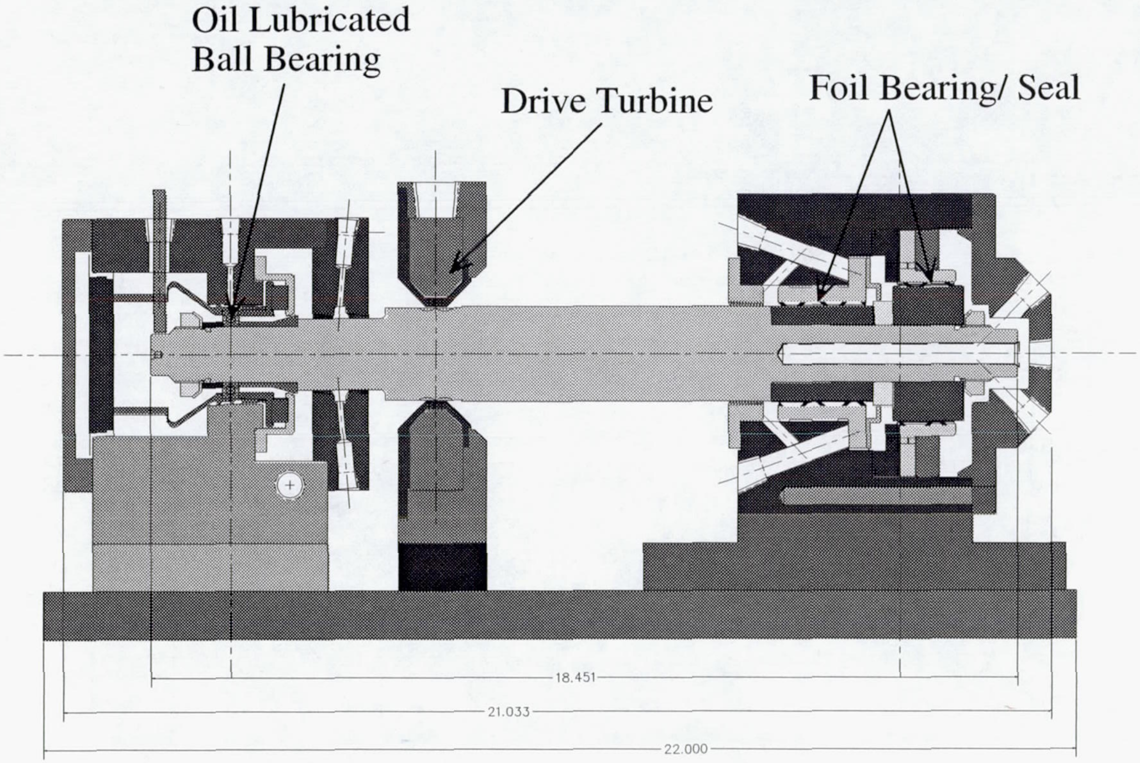
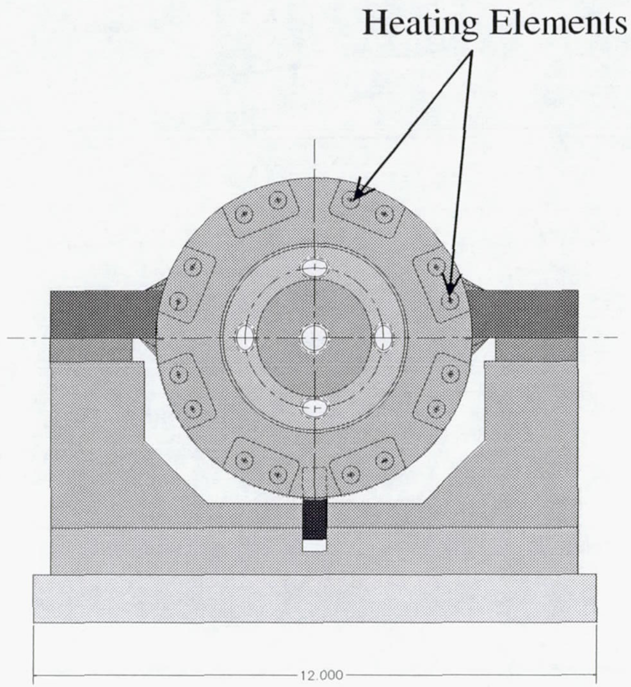
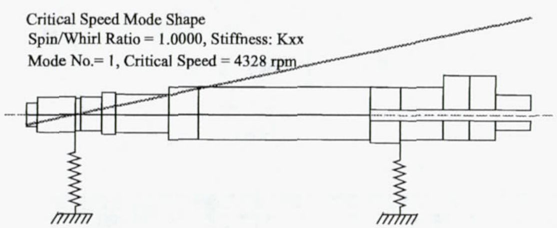
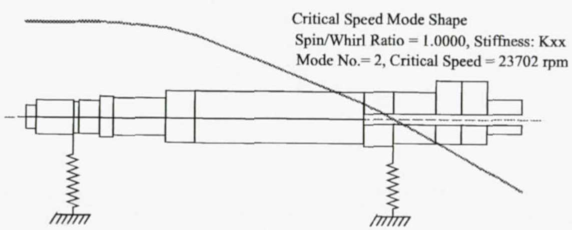
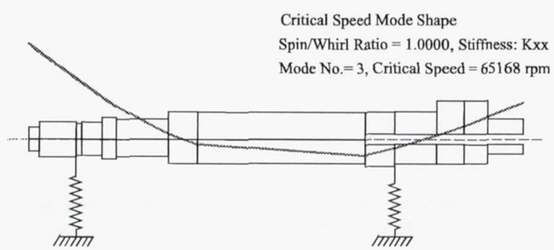
High Temperature Hybrid Bearing/Seal Dynamic Simulator











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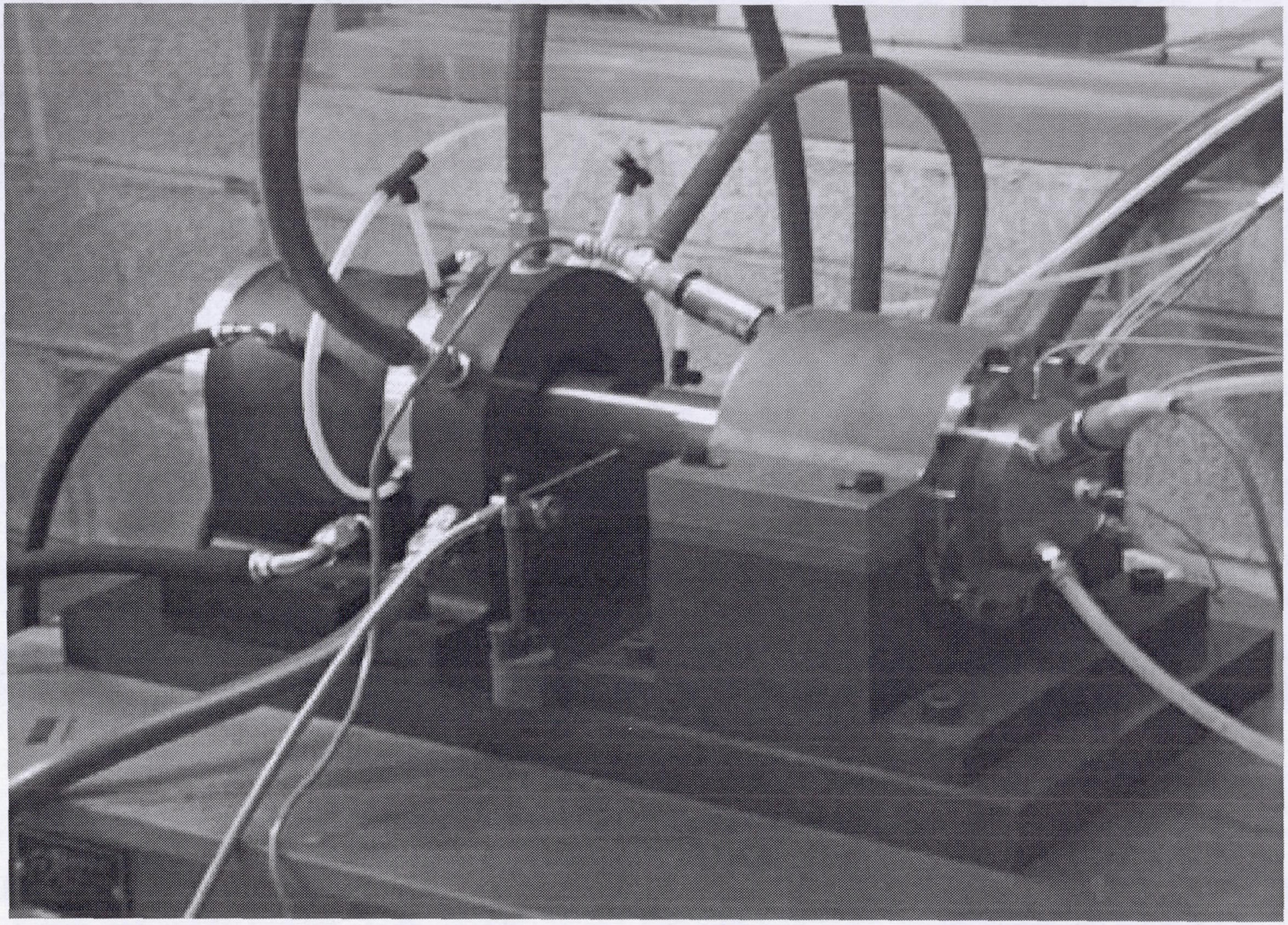
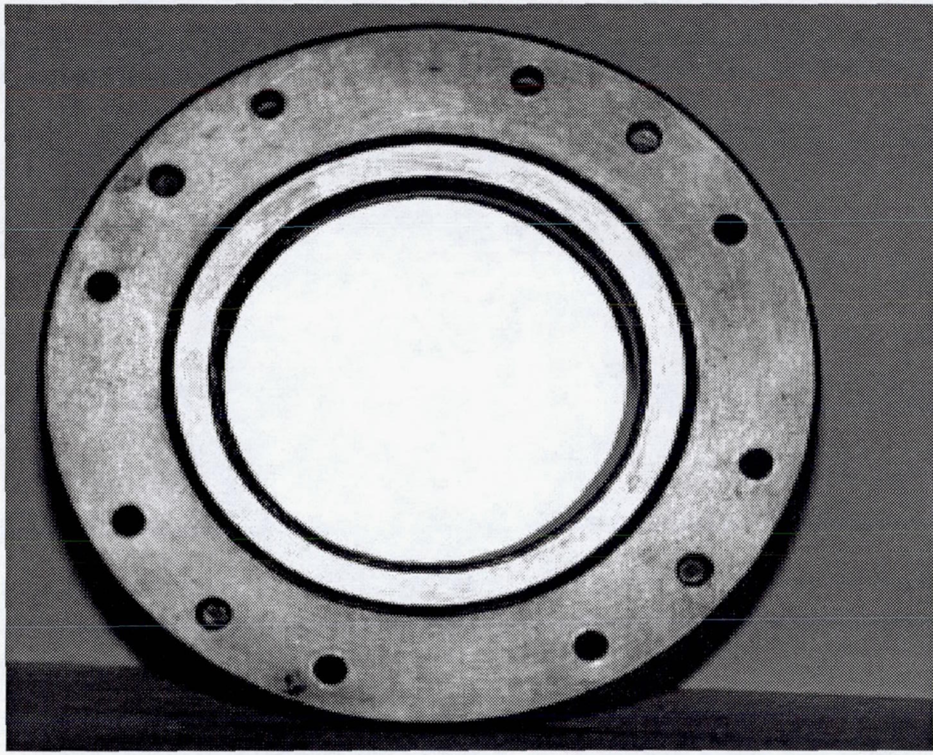
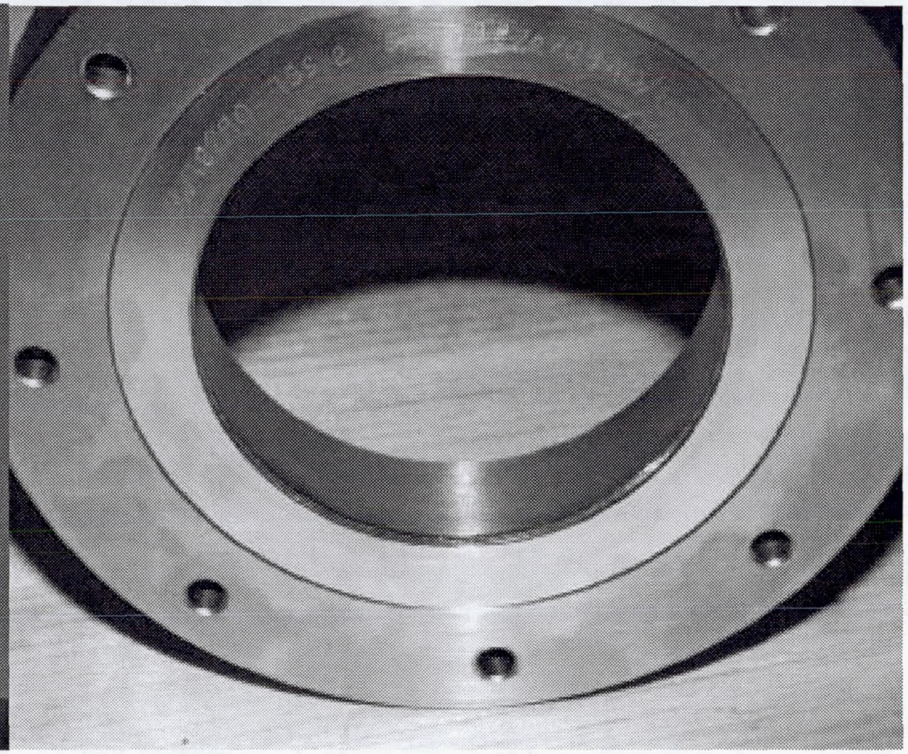
Instrumented Test Apparatus



Seals -Tested



Compliant Foil Seal



Brush Seal

Fabricated by Cross MNFG CO. LTD

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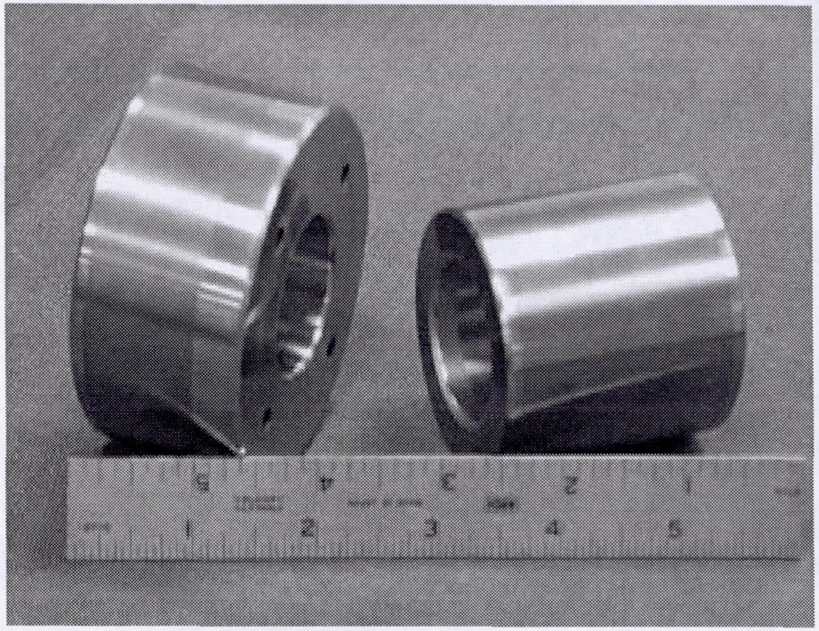
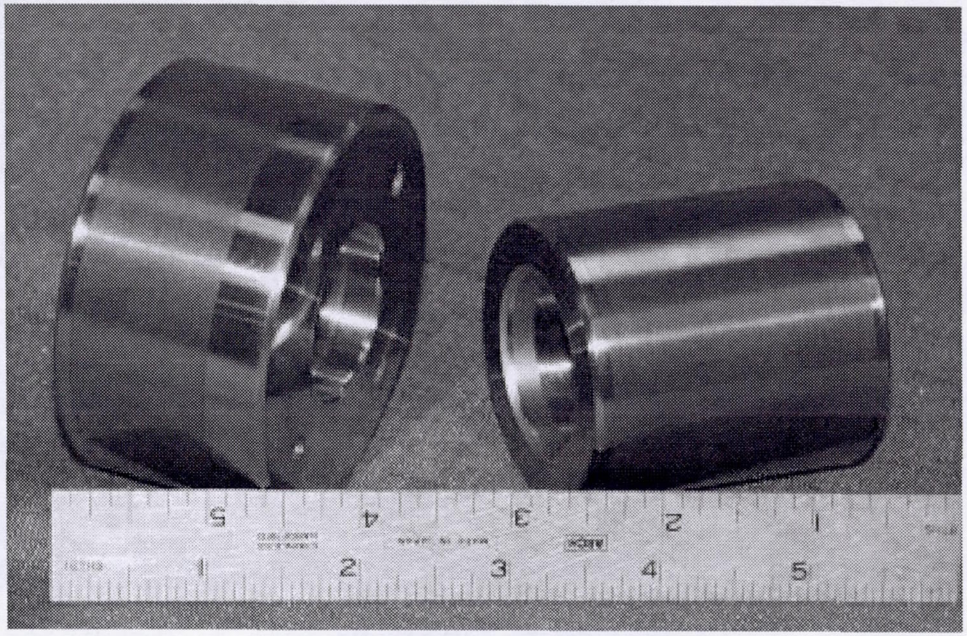
Journals for Compliant Surface Foil Seal/Bearing



Low Temperature Journals



High Temperature Journals

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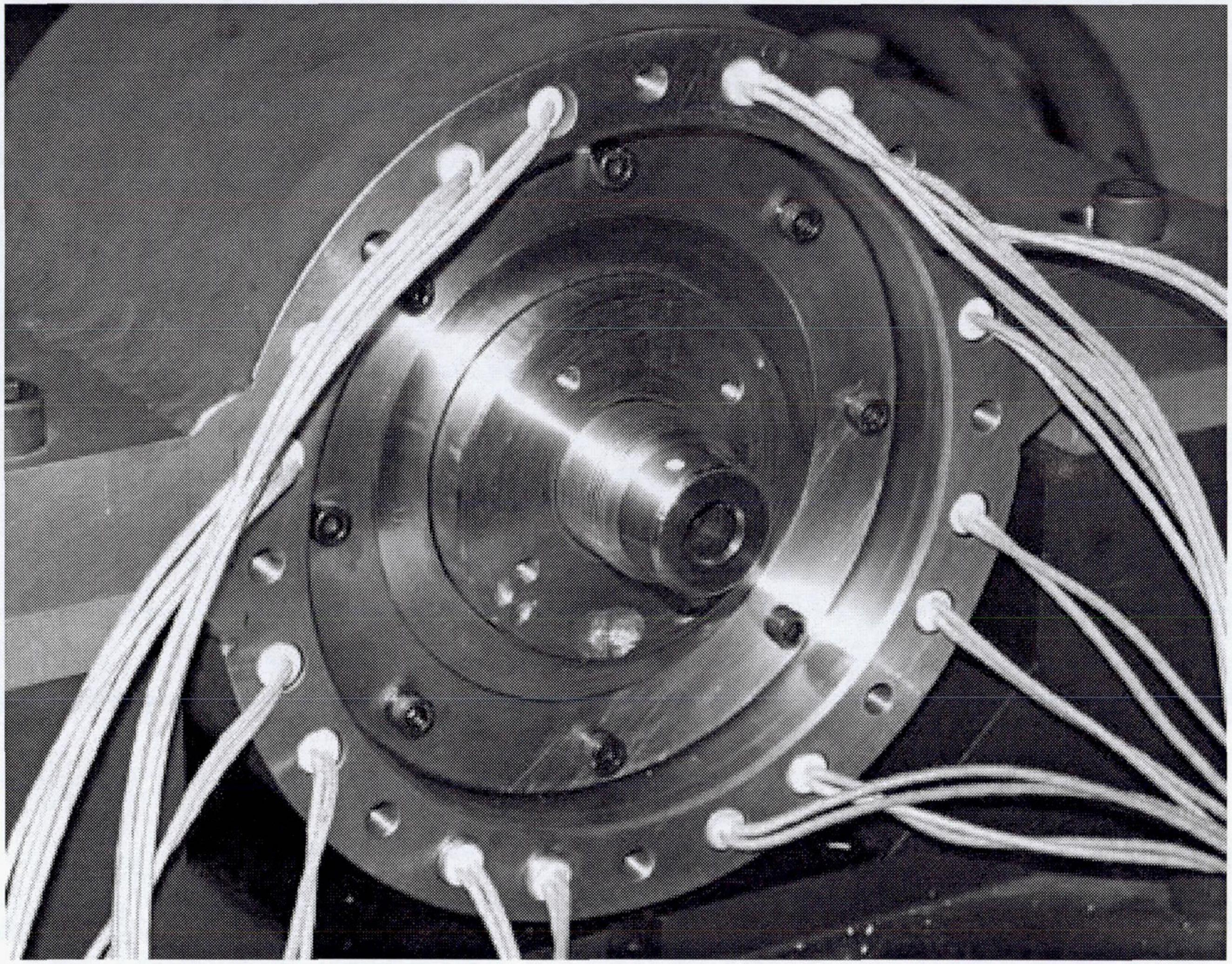
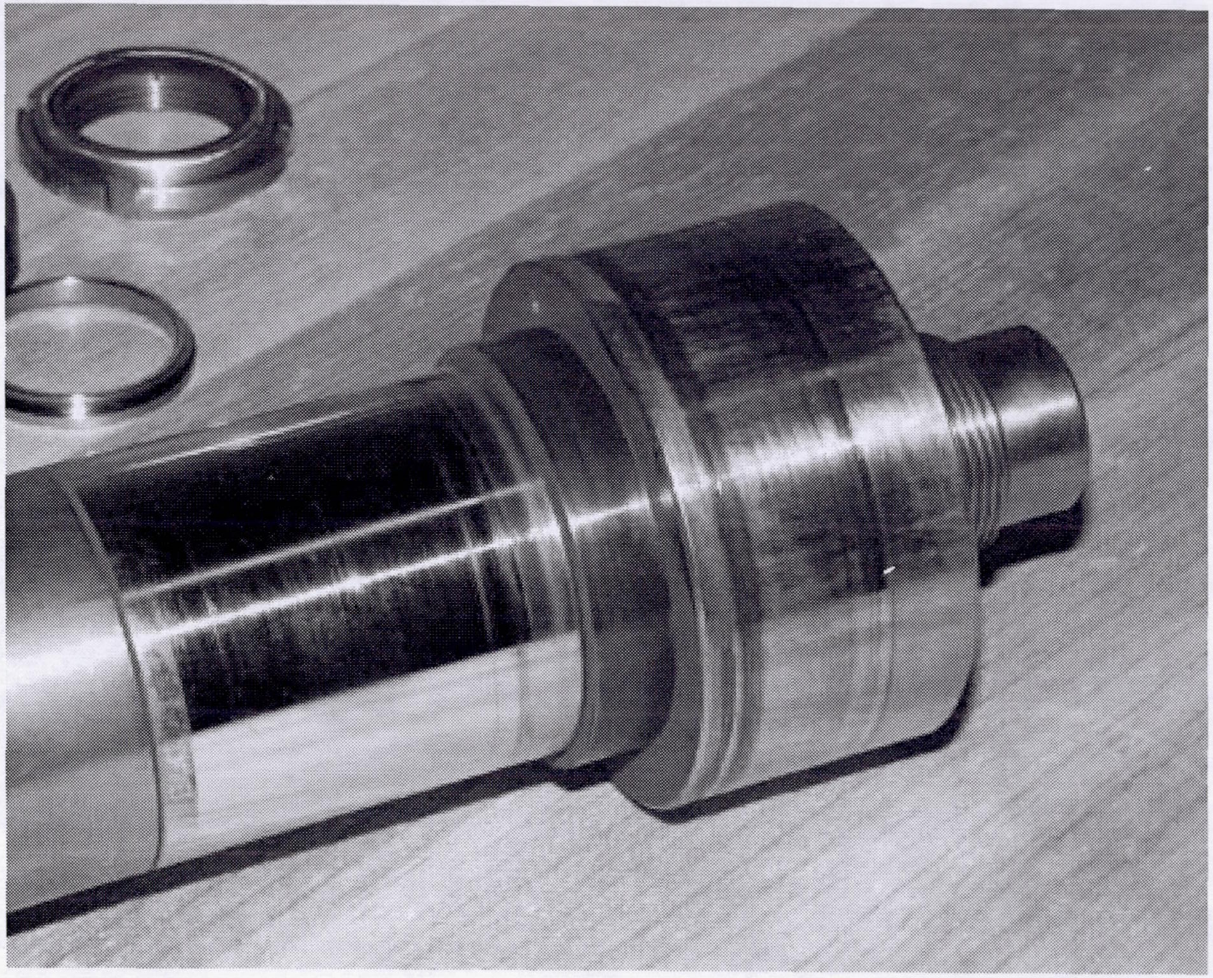
Mounted Brush Seal

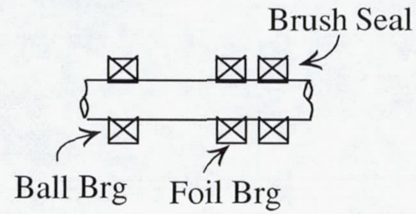


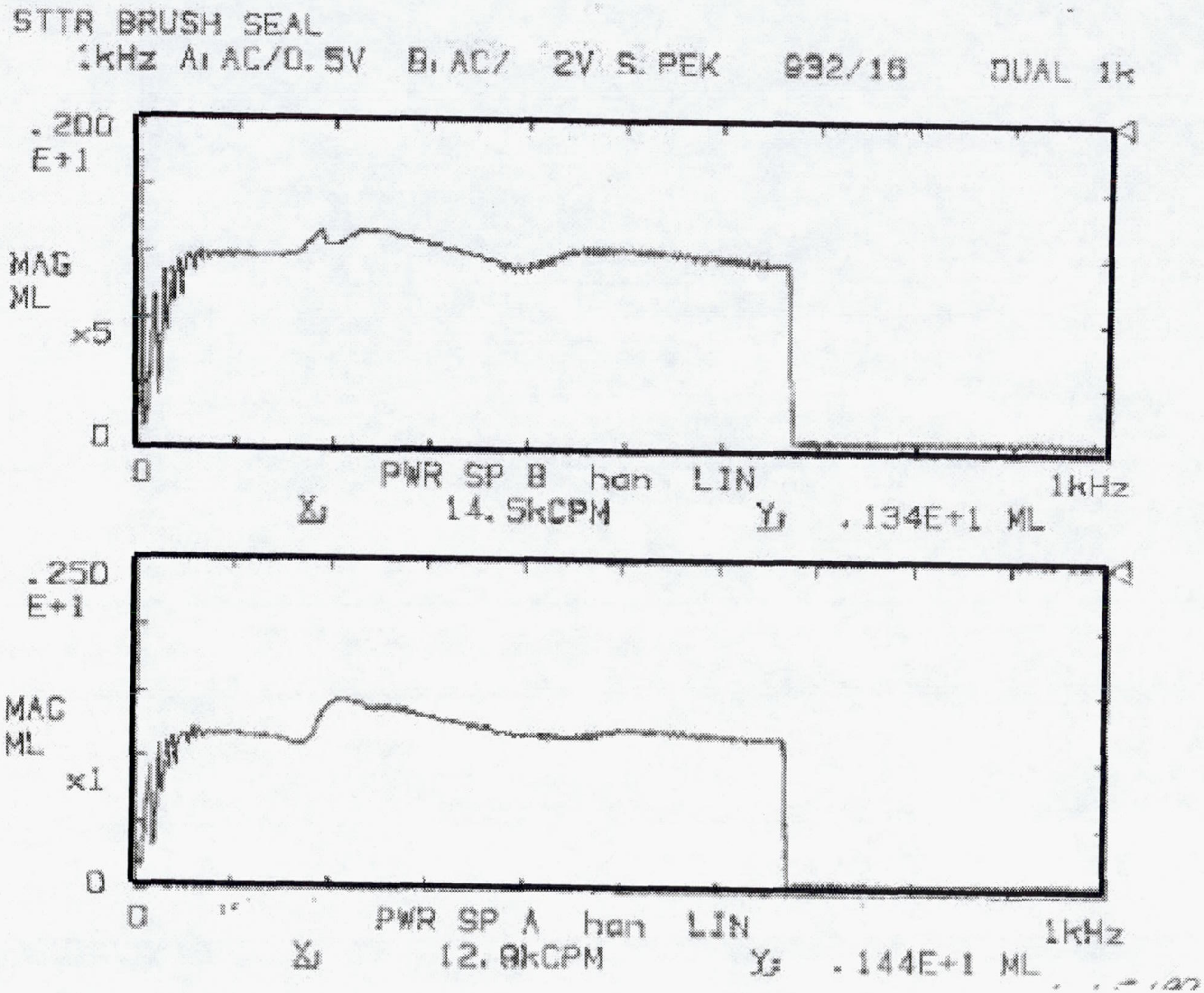
Wear Track from the Brush Seal



Coastdown on Brush Seal

Max. Speed = 41,000 rpm
Max. Orbit size = 1.6 mil

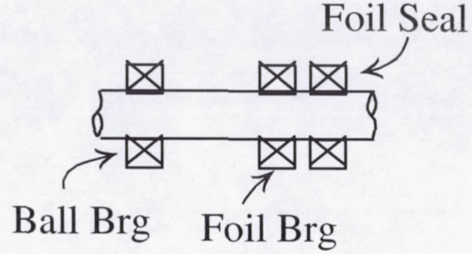




Coast Down at 56,000 rpm

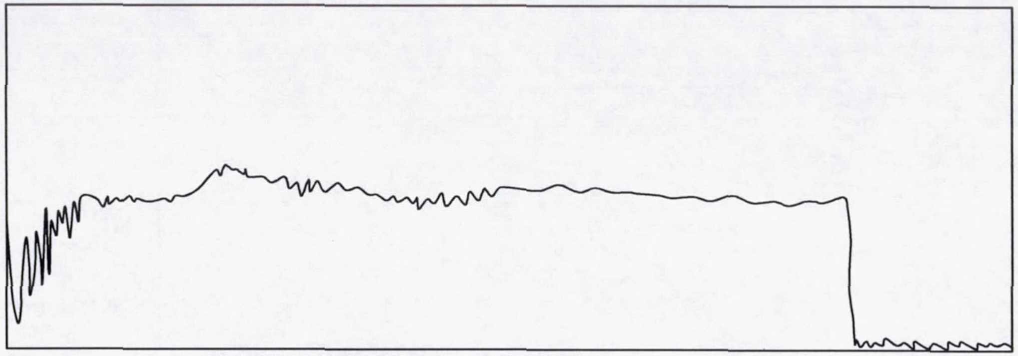
NASA/CP—2000-210472/VOL1

1kHz A: AC/ 1V B: AC/ 1V S.PEK 1200/8 DUAL 1k



.250
E+1

MAG
ML



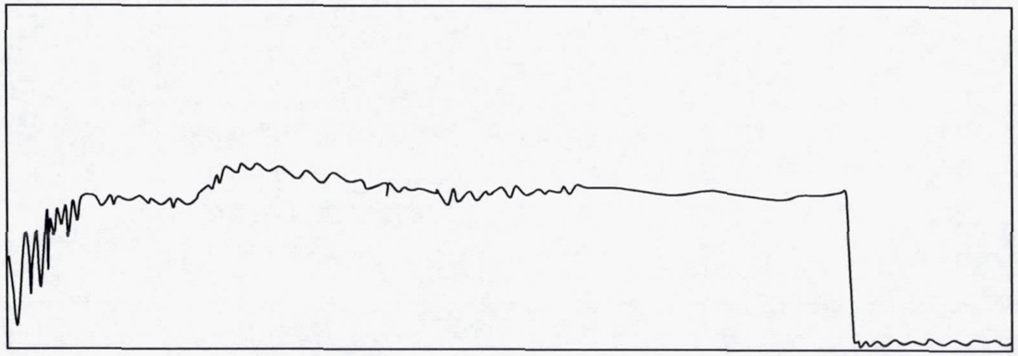
PWR SP B LIN 1kHz

X: 12.9kCPM Y: .134E+1 ML

.250
E+1

MAG
ML

0

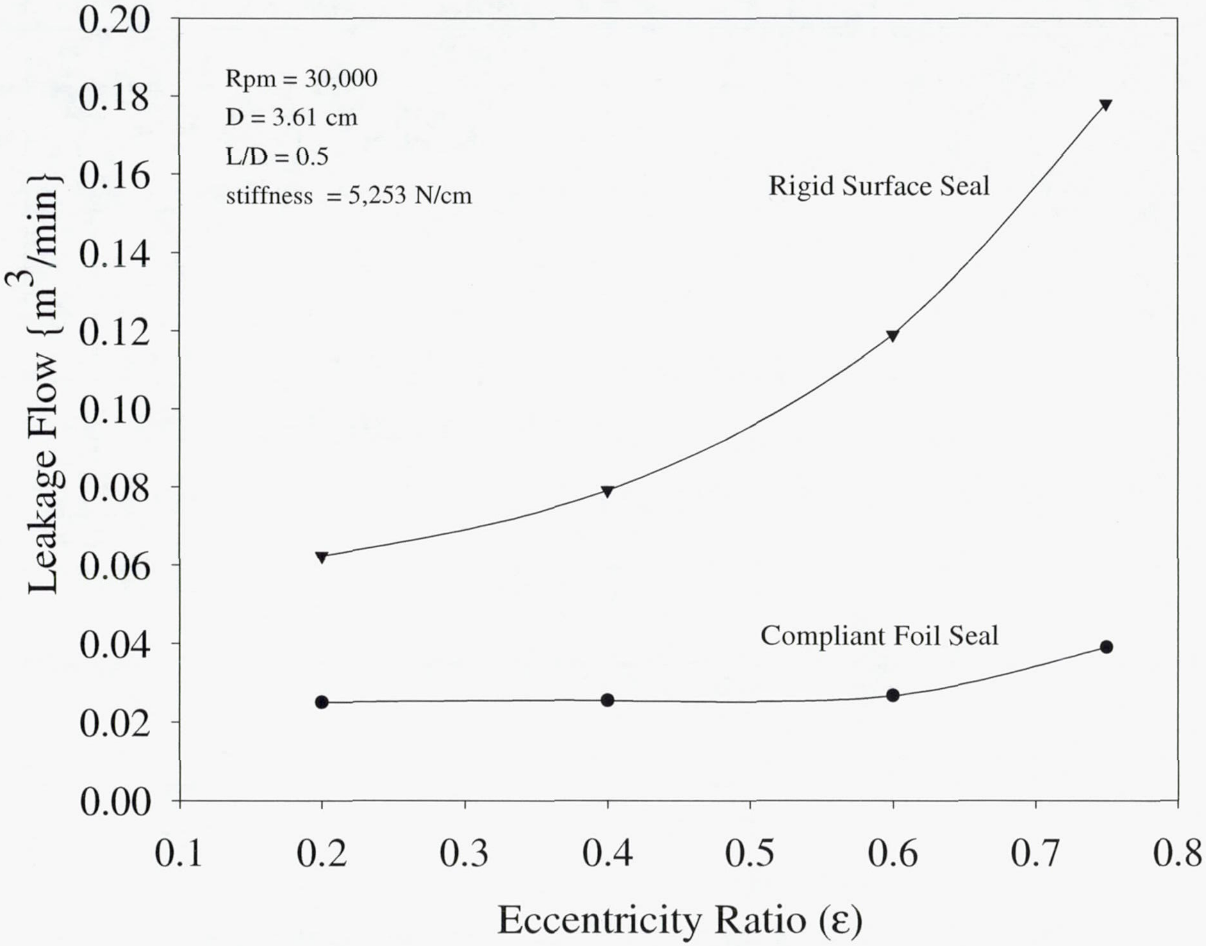


0 PWR SP A LIN 1kHz

X: 14.7kCPM Y: .137E+1 ML

Run : T7R1

Analysis Prediction for Compliant vs Rigid Surface Seal



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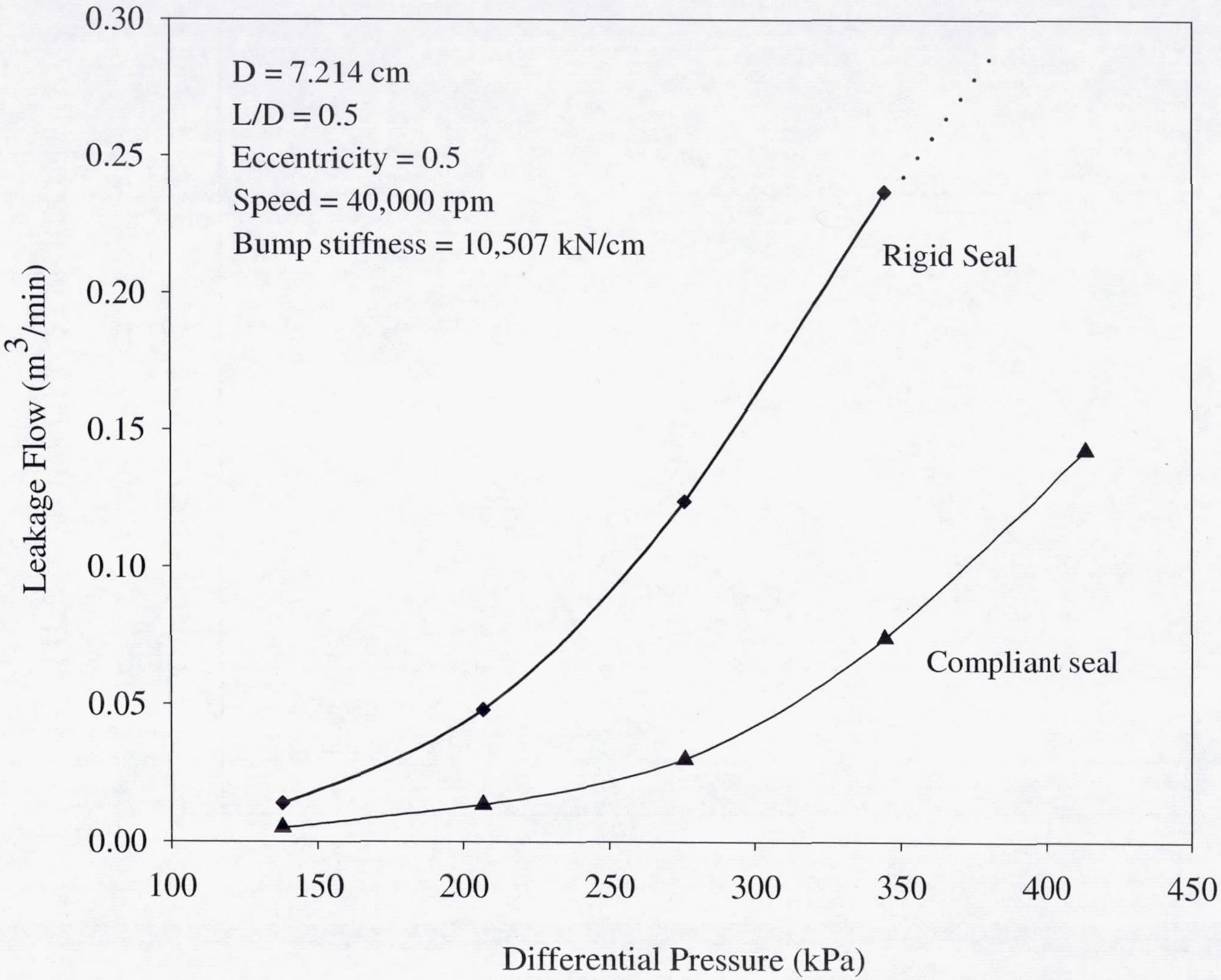
Analysis Prediction for Compliant vs Rigid Surface Seal



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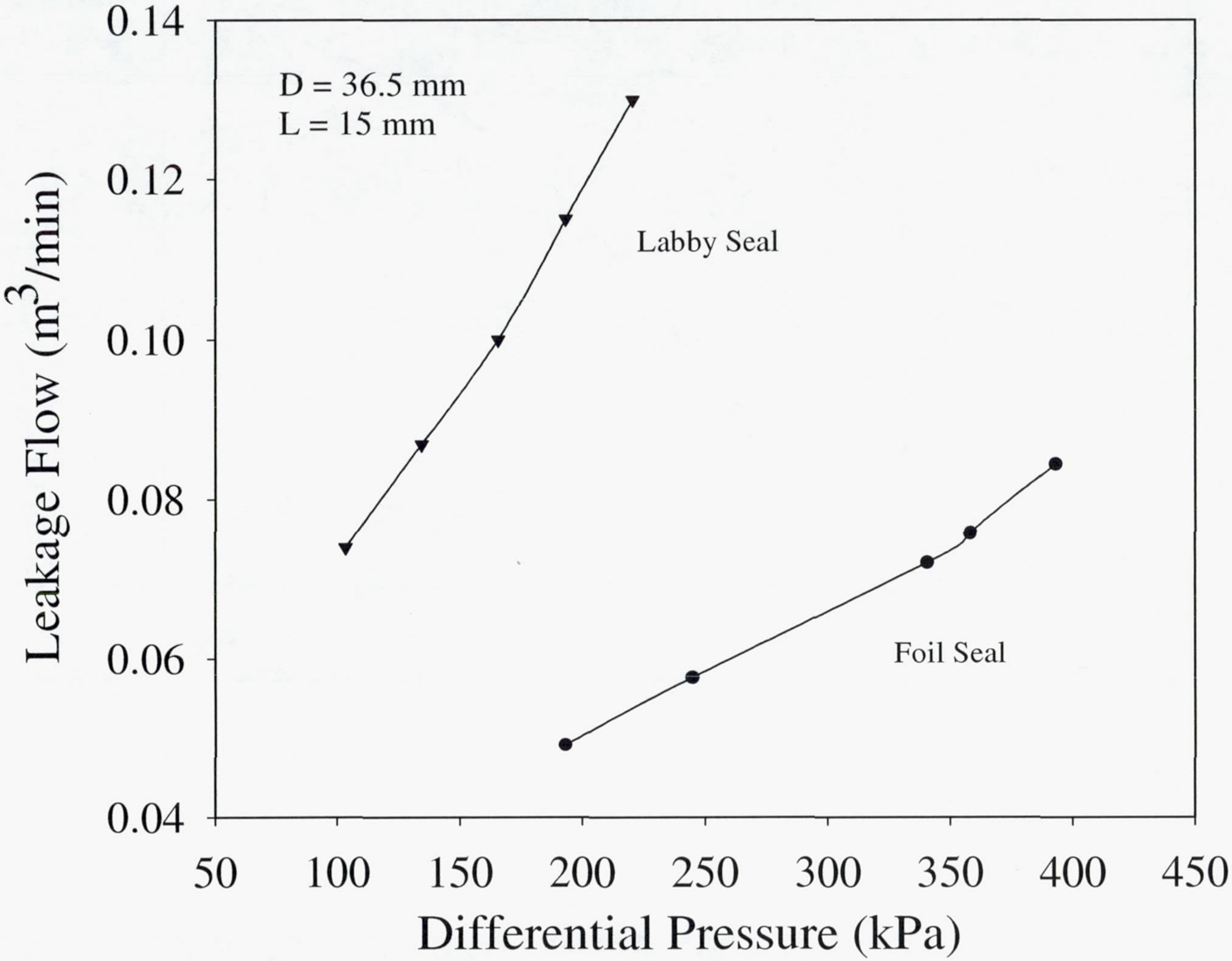
Compliant Seal vs Labby Seal - Static Test



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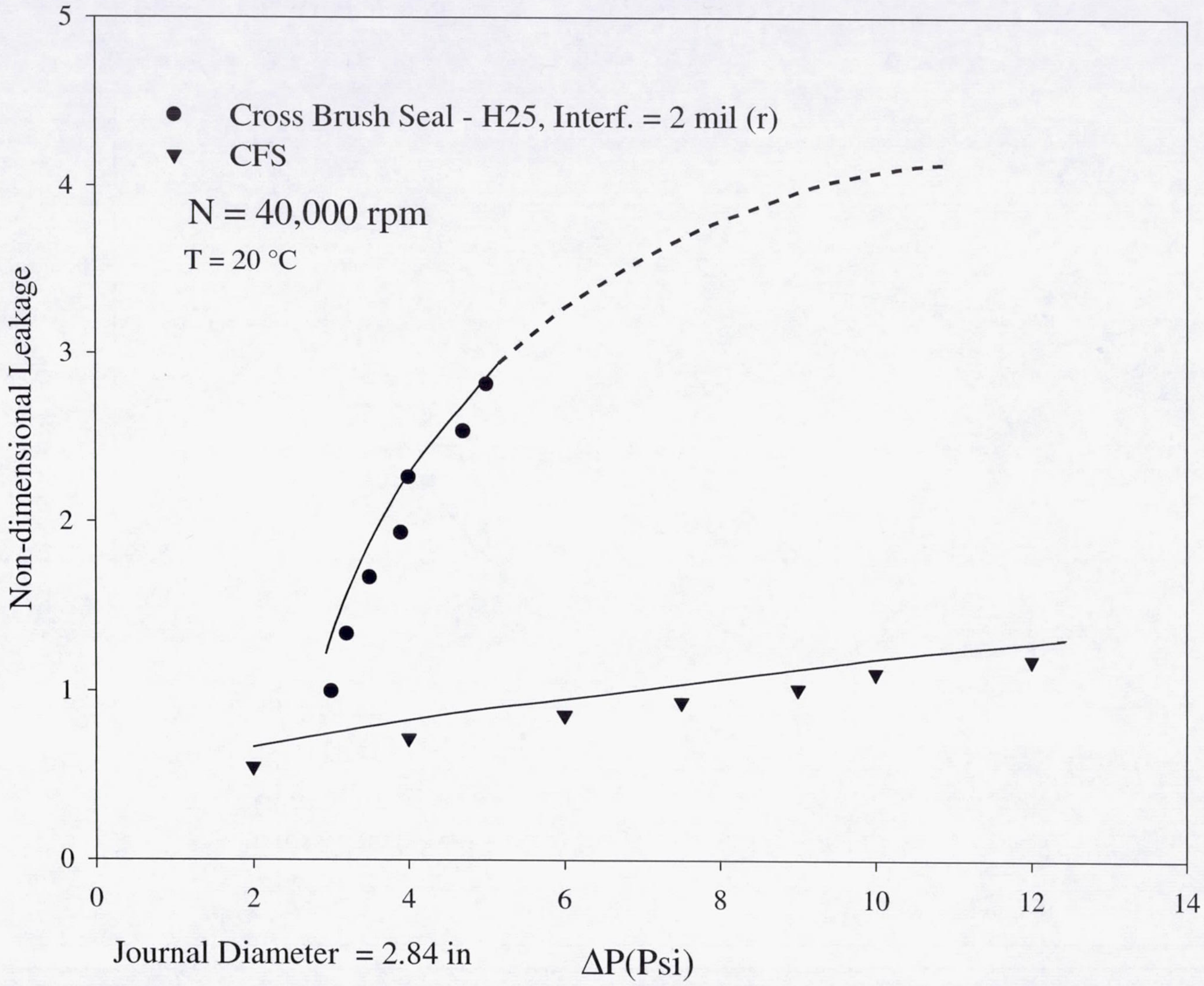
Compliant Foil Seal vs Cross™ Brush Seal



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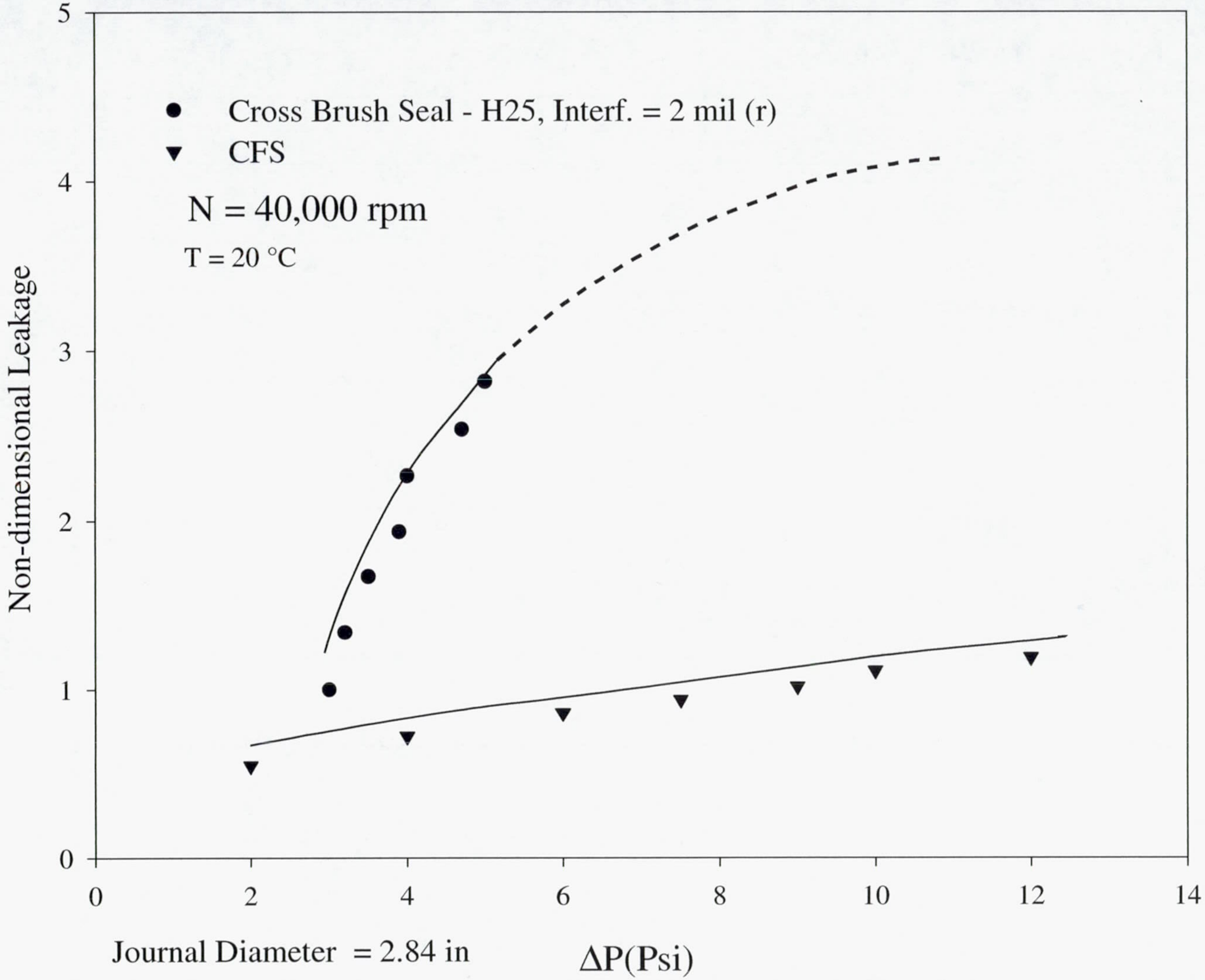
Compliant Foil Seal vs Cross™ Brush Seal



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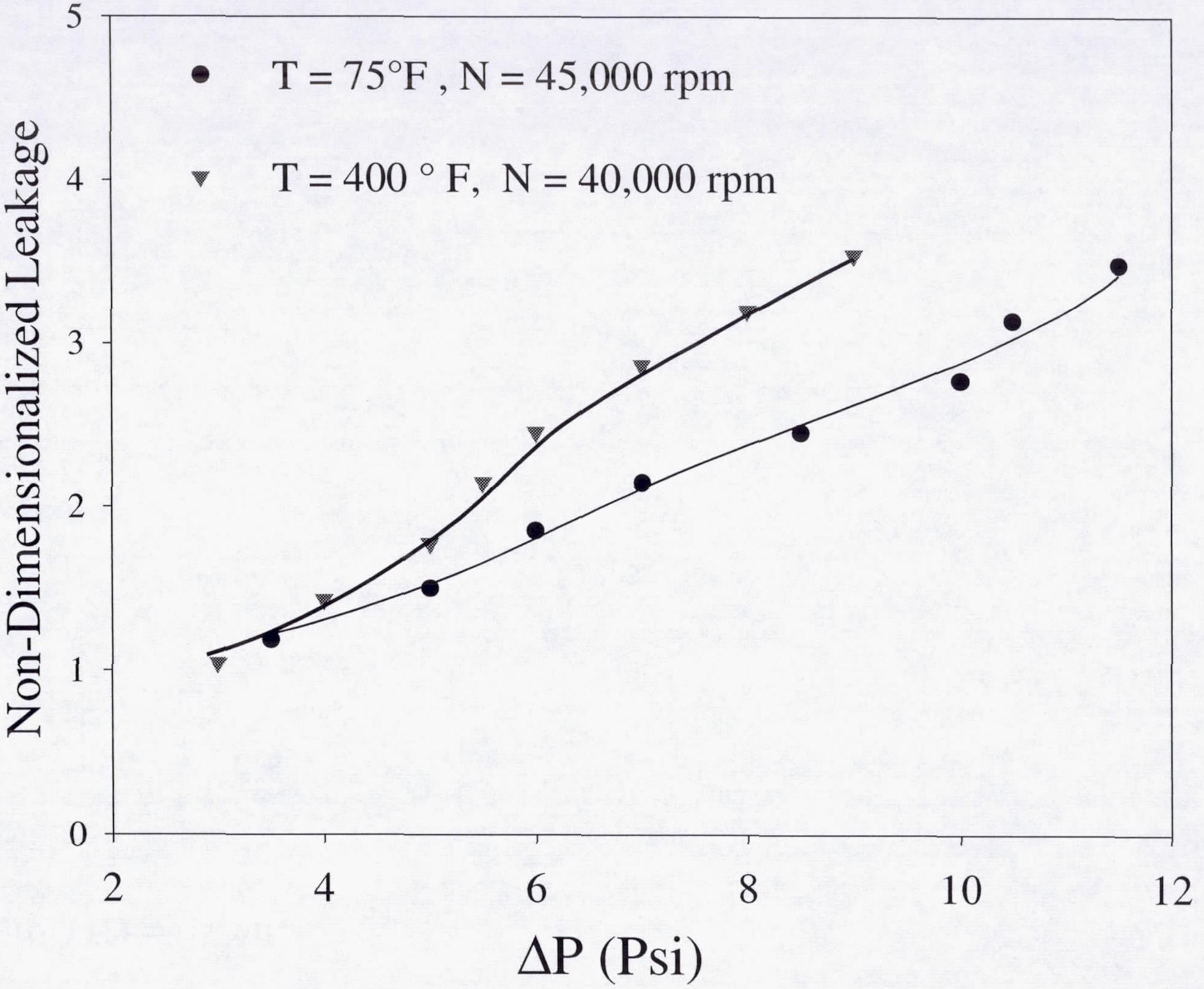
Compliant Seal Performance - Temperature Effect



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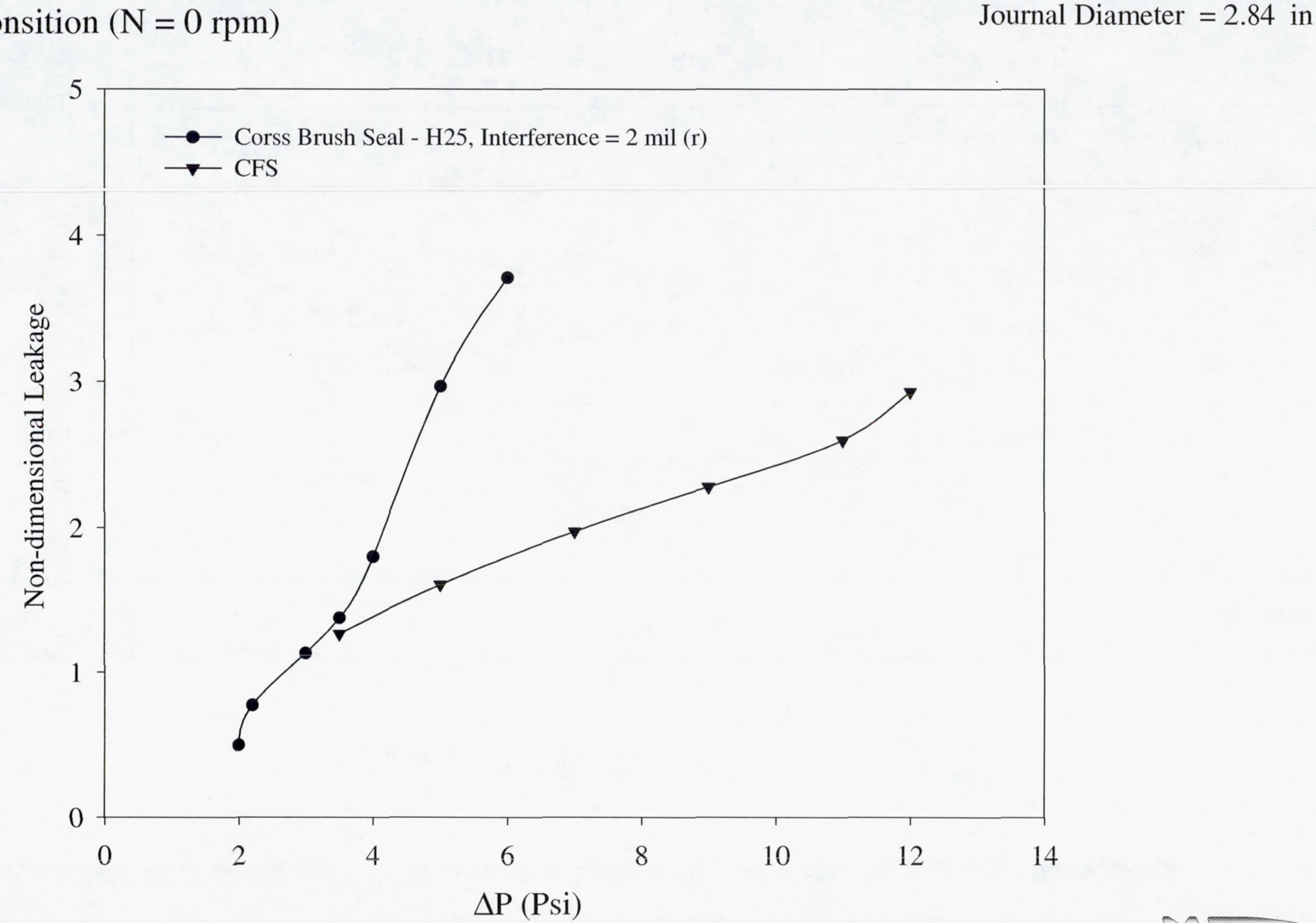
Compliant Foil Seal vs Cross™ Brush Seal



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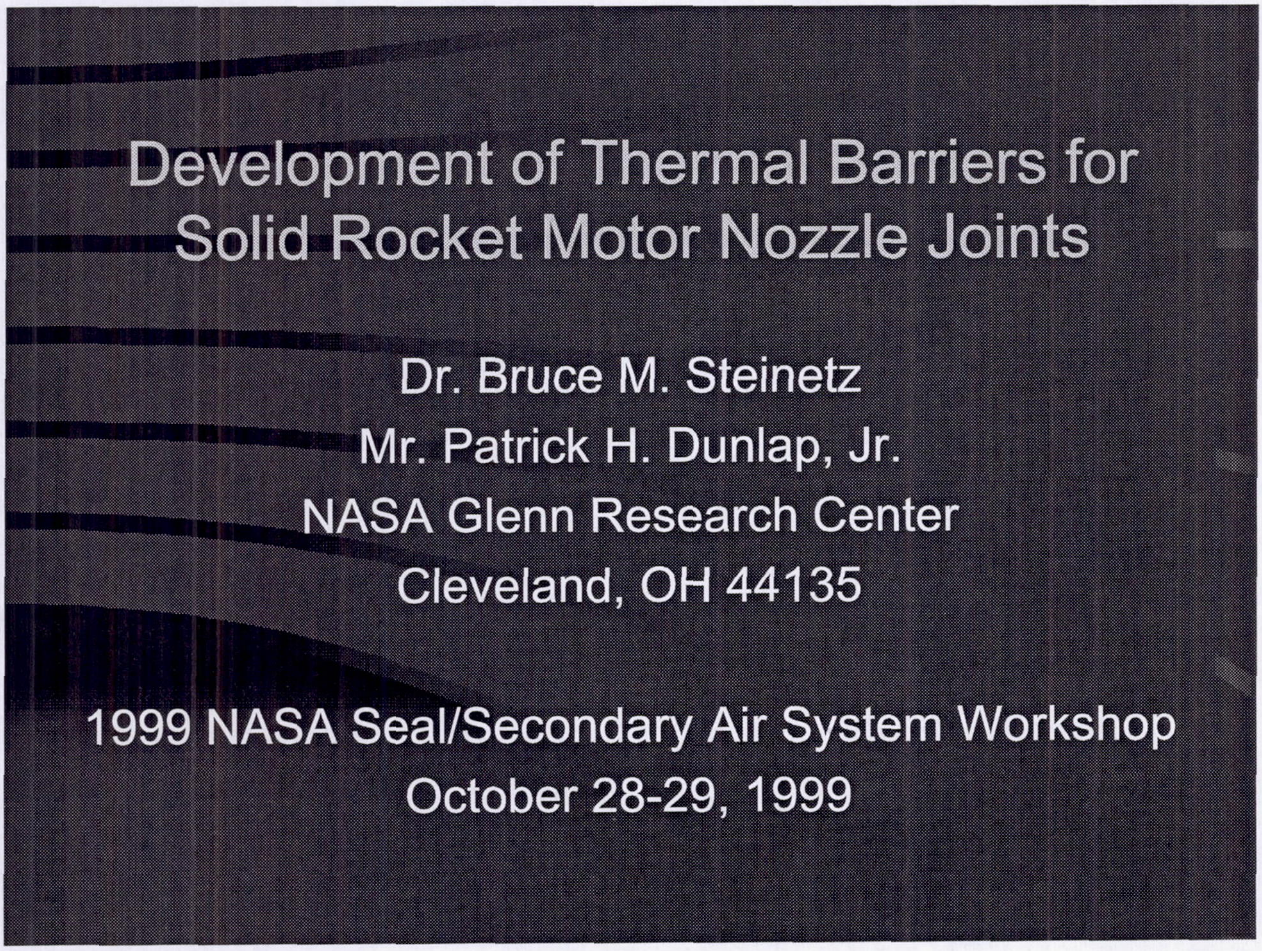
DEVELOPMENT OF THERMAL BARRIERS FOR SOLID ROCKET MOTOR NOZZLE JOINTS

Bruce M. Steinetz and Patrick H. Dunlap, Jr.
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio



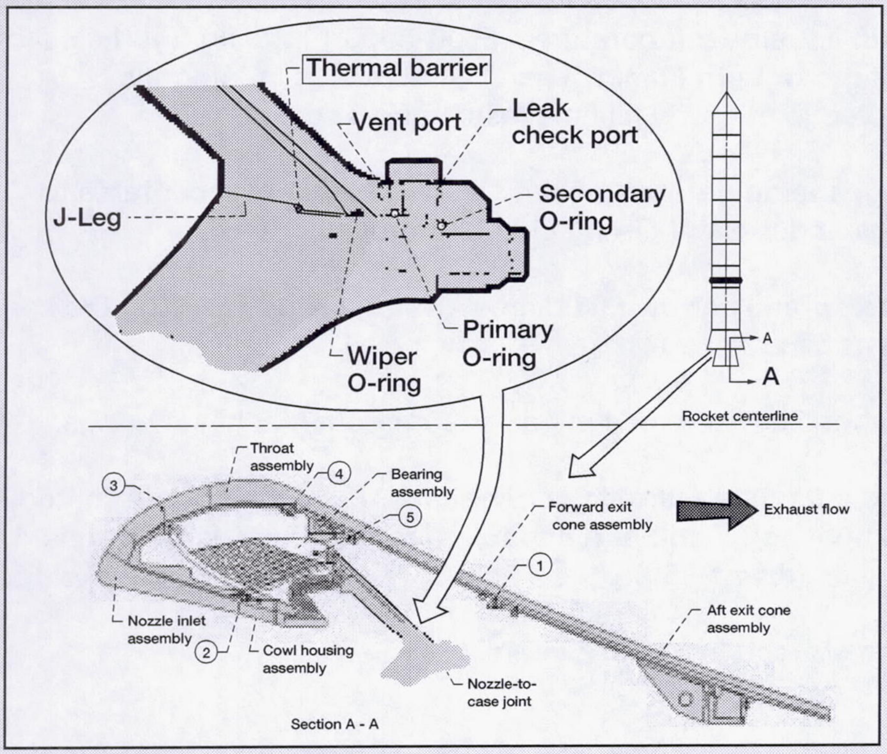
Background

- Shuttle RSRM Joints are sealed with O-rings to contain rocket pressure (to 900 psi) and prevent outflow of high temperature (5500 °F) combustion gases. Motors are insulated with either phenolic or rubber insulation. Joint gaps are generally filled with joint-fill compounds.
- Current RSRM nozzle-to-case joint design incorporating primary, secondary, and wiper O-rings, expected to experience gas paths through the joint-fill compound (polysulfide) to the inner-most wiper O-ring in about 1 out of 7 motors.
- Hot gas flow to the wiper O-ring is an undesirable condition that Thiokol/NASA wants to eliminate. Though it poses no safety hazard to the motor, each nozzle-to-case joint gas path results in extensive reviews and evaluation requiring close-out prior to resuming flight.
- Thiokol/NASA Marshall are currently working to improve the nozzle-to-case joint design by implementing the more reliable J-Leg design (used successfully in field and igniter joints), NASA Glenn thermal barrier, and eliminate the joint-fill compound.

CD-98-77995a

Joints in the Space Shuttle solid rocket motors are sealed by O-rings to contain combustion gases inside the rocket that reach pressures of up to 900 psi and temperatures of up to 5500°F. To provide protection for the O-rings, the motors are insulated with either phenolic or rubber insulation. Gaps in the joints leading up to the O-rings are filled with polysulfide joint-fill compounds as an additional level of protection. The current RSRM nozzle-to-case joint design incorporating primary, secondary, and wiper O-rings experiences gas paths through the joint-fill compound to the innermost wiper O-ring in about one out of every seven motors. Although this does not pose a safety hazard to the motor, it is an undesirable condition that NASA and rocket manufacturer Thiokol want to eliminate. Each nozzle-to-case joint gas path results in extensive reviews and evaluation before flights can be resumed. Thiokol and NASA Marshall are currently working to improve the nozzle-to-case joint design by implementing a more reliable J-leg design that has been used successfully in the field and igniter joints. They are also planning to incorporate the NASA Glenn braided carbon fiber thermal barrier into the joint. The thermal barrier would act as an additional level of protection for the O-rings and allow the elimination of the joint-fill compound from the joint.

SRM Nozzle-to-Case Joint:
Potential Location for NASA Glenn Thermal Barrier



CD-98-78006b

This chart shows where Thiokol plans to use the thermal barrier in the nozzle-to-case joint of the Shuttle solid rocket motor. The figure at the bottom is an enlarged area of the rocket nozzle showing the nozzle-to-case joint and nozzle joints one through five. Thiokol has recently begun an aggressive plan to qualify the thermal barrier for use in Joint 2 and is considering using it in other nozzle joints. The figure at the top is an enlarged view of the nozzle-to-case joint. The primary, secondary, and wiper O-rings are shown along with the phenolic insulation (in orange) and the surrounding metal hardware (in blue). The J-leg in the insulation is also indicated. The thermal barrier is highlighted in its position upstream of the O-rings where it would help block hot combustion gases from reaching the O-rings.

Thermal Barrier Has Unique Requirements

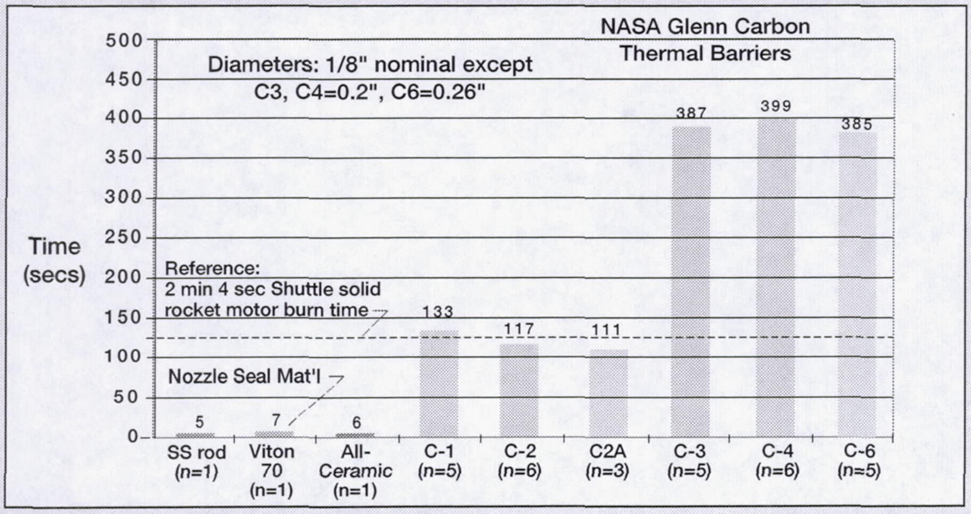
- Sustain extreme temperatures (2500-5500°F) during Shuttle solid rocket motor burn (2 min. 4 sec.) without loss of integrity. Expected joint cavity fill time less than 10 sec.
- Drop gas temperatures in joint (3200°F) to levels acceptable to Viton O-rings and prevent O-ring char and erosion.
- Diffuse/spread narrow (.08 diameter) hot gas jet reducing the energy/unit area.
- Block hot slag entrained in gas stream from reaching O-rings.
- Exhibit adequate resiliency/springback to accommodate limited joint movement and manufacturing tolerances in these large nozzle segments (diam. 8.5').
- Endure storage for up to 5 years.

CD-98-77996b

To be used in the nozzle-to-case joint of the Shuttle solid rocket motors, the thermal barrier has several unique requirements. It must be able to withstand extreme temperatures of up to 5500°F during the Shuttle solid rocket motor burn time of 2 minutes 4 seconds without loss of integrity. Although the rocket burns for over two minutes, the thermal barrier actually only has to endure these extreme temperatures for less than ten seconds. As hot gases flow through the permeable thermal barrier, they fill the cavity between the thermal barrier and the downstream wiper O-ring. Once the pressure across the thermal barrier equilibrates, hot gases stop flowing into the cavity. Therefore, the thermal barrier must be able to drop the hot gas temperature in the joint to levels that the Viton O-rings can withstand to protect the O-rings from charring and erosion. The thermal barrier also has to be able to diffuse and spread narrow hot gas jets with diameters of 0.08 inches to prevent them from impinging on the O-rings. The thermal barrier has to filter hot slag out of the gas stream to prevent it from reaching the O-rings. It must exhibit adequate resiliency to accommodate limited joint movement and manufacturing tolerances in these large nozzle segments with diameters of 8.5 feet. Finally, the thermal barrier has to be able to endure storage for up to five years. Once the rockets are assembled, they often sit for several years before they are used.

Burn Time of Candidate Thermal Barrier Materials

Oxyacetylene Torch Results



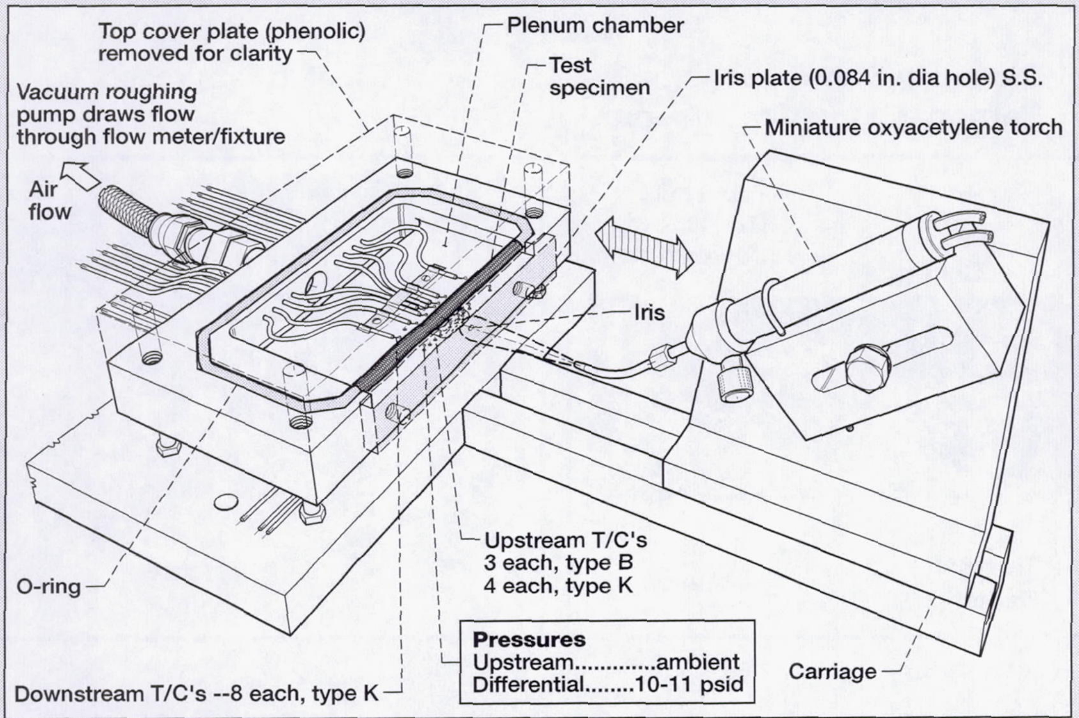
- NASA Glenn braided carbon thermal barrier (C-6) resists flame for over 6 minutes: Expected joint cavity fill time ≤ 10 sec
- Anticipated carbon barrier mass-loss mechanism: Carbon fiber oxidation
  - Carbon sublimation temperature (6900°F) > Rocket hot gas temperature (5500°F)
- Test believed to be conservative for carbon thermal barriers as rocket exhaust chemistry is less oxidative than torch burn test

CD-98-77998b

When Thiokol first approached NASA Glenn about this problem, we devised a simple test to screen different thermal barrier materials and designs. Candidate materials were subjected to a test in which specimens were placed into the flame of an oxy-acetylene torch and the amount of time to completely burn through them was measured. The torch was adjusted until a neutral flame was formed, and the thermal barrier materials were placed in the hottest part of the flame at the tip of the inner cone where temperatures reached 5500°F. This chart shows the results of burn tests performed on candidate thermal barrier materials and designs. It shows the amount of time that it took for the oxyacetylene torch to cut completely through the different materials. All of the specimens were 1/8" in diameter except the Carbon-3 (C-3) and Carbon-4 (C-4) designs, which were 0.2" in diameter, and the Carbon-6 (C-6) design that was 0.26" in diameter. Thiokol is evaluating the C-6 design for the nozzle-to-case joint and for Joint 2. The first specimen that was tested was a 1/8" diameter stainless steel rod to get a reference point on how hot the flame was. This rod was cut through in only 5 seconds, and the metal was actually melted where the flame cut through. Next, a 1/8" diameter Viton O-ring, the same material used for the O-rings in the rocket nozzle, was tested. It was cut through in about 7 seconds. An all-ceramic seal design was tested next, and it only lasted 6 seconds in the flame. At this point, we realized that we needed to evaluate other material systems, so we designed arrangements braided out of carbon fibers. The three 1/8" diameter carbon fiber designs all lasted about 2 minutes in the oxyacetylene flame. As a point of comparison again, the Shuttle solid rocket motor burn time of 2 minutes 4 seconds is indicated in the figure. Moving up in diameter, the C-3 and C-4 designs with diameters of 0.2" and the C-6 design at 0.26" lasted about six and a half minutes in the flame. Thus, these thermal barriers can endure 5500°F gases for over three times longer than the solid rockets are actually in operation. After the carbon thermal barriers were removed from the flame, the areas where the flame cut through them were just as soft and flexible as before they were tested. There were no signs of melting, charring, or embrittlement. We believe that the carbon fibers were actually being oxidized as they were cut through. Carbon fibers oxidize at temperatures above 600 to 900°F depending on the type of fiber. At the other end of the spectrum, the sublimation temperature of carbon is 6900°F. Therefore, the temperature of the rocket and the oxyacetylene torch at 5500°F is hot enough for oxidation of the fibers but not hot enough for sublimation to occur. Also, these tests are probably conservative in terms of burn resistance because they were performed in an oxidizing ambient atmosphere. The rocket exhaust chemistry is not as oxidative, though. It is possible that the carbon thermal barriers could be exposed to rocket exhaust in the Shuttle solid rocket motors and not even be effected.

This chart shows the thermal barrier while it is being exposed to the oxyacetylene torch. An incandescent fireball can be seen around the thermal barrier, which is positioned at the tip of the inner cone of the flame. In actuality, this fireball is too bright to look at with the naked eye, and welding glasses must be used to view the test. However, this image was taken with a digital camera that filtered out the brightness of the flame.

Temperature Drop Test Fixture

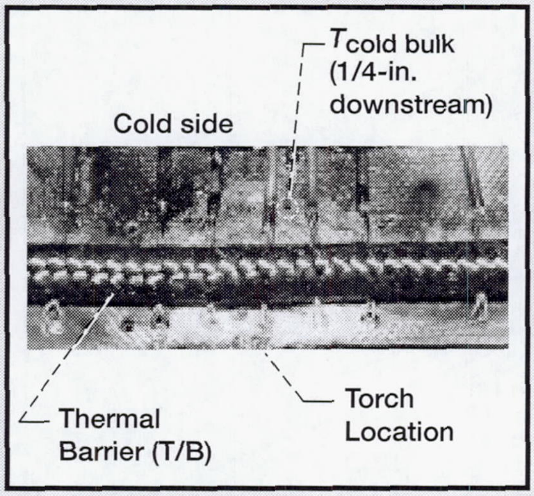


CD-99-79224

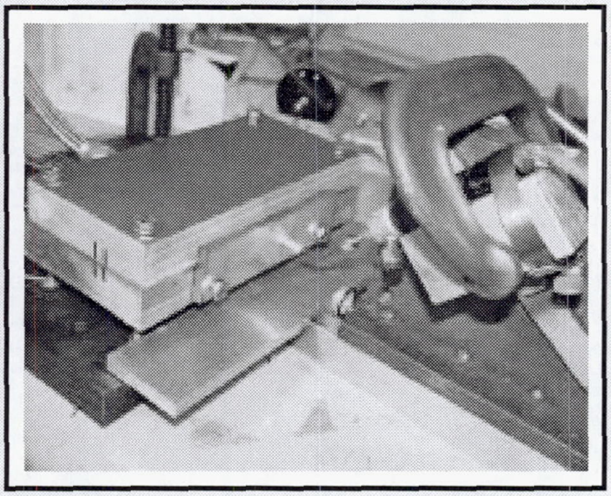
Although the burn tests showed that the carbon thermal barrier designs could resist extreme temperatures for extended periods of time, a test method was required that would more accurately simulate the conditions that the thermal barrier would be subjected to in a rocket. Therefore, we designed a new fixture to measure the temperature drop across and along the thermal barrier in a compressed state when subjected to narrow jets of hot gas at upstream temperatures of 3000°F. The thermal barrier was compressed between two plates of phenolic material to simulate the insulation of the solid rocket motors. Specimens were instrumented with thermocouples on both their upstream and downstream sides to measure the temperature drop across and along the specimen when it was exposed to a hot gas jet from a miniature oxyacetylene torch. An "iris plate" was secured between the torch and the specimen, and a hole in this plate focussed the flame of the torch into a narrow 0.08-inch diameter jet. A vacuum roughing pump hooked up to the plenum chamber downstream of the specimen ensured that hot gas flow from the torch was drawn through the specimen. A flow meter downstream of the fixture measured the amount of flow that passed through the specimen during a test. Pressure transducers measured the upstream pressure (ambient) and differential pressure (10-11 psid) across the specimen. Tests were typically conducted for about a thirty-second torch application.

Temperature Drop Fixture Photographs

Close-Up Showing Thermal Barrier and Instrumentation



Test in Progress



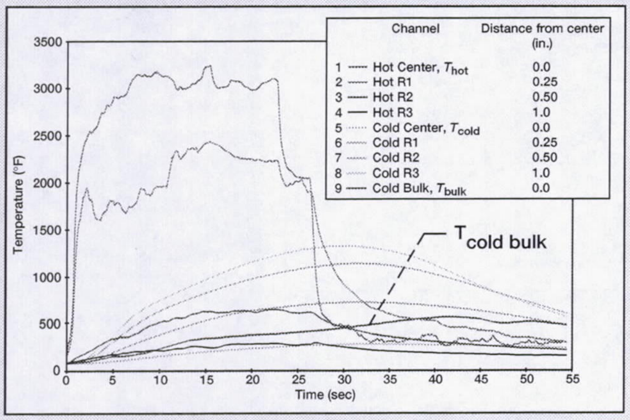
CD-99-79225

This chart shows two photographs of the temperature drop test fixture. The photo on the left shows a specimen as it is instrumented with thermocouples. A pair of thermocouples was aligned directly in the center of the hot gas jet on the upstream and downstream sides of the specimen. Additional thermocouples were placed 1/4", 1/2", and 1" away from the center thermocouples on both sides of the specimen. The tips of the thermocouples were tucked into the outermost sheath layer to measure the surface temperature of the specimen during a test. An additional thermocouple was located 1/4" downstream of the specimen in line with the center thermocouples to measure the temperature drop one specimen diameter downstream. This was referred to as the "cold bulk" temperature.

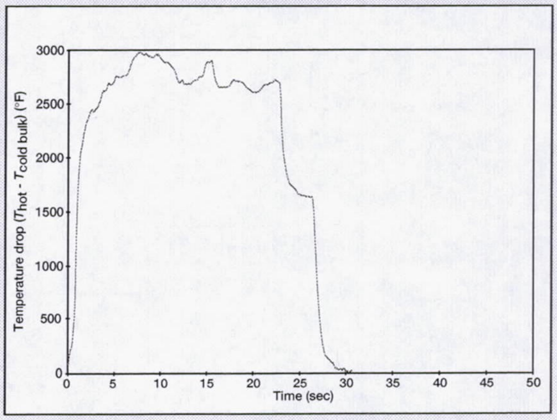
The photo on the right shows the fixture as the torch is being moved toward the iris plate.

Temperature Drop Test Results: C-6

Temperature vs. Time
Hot/Cold Sides and $T_{cold\ bulk}$



Temperature Drop
(T_{hot} - $T_{cold\ bulk}$) vs. Time



$T_{cold\ bulk}$ = Temperature 1/4-in. downstream, aligned with centerline of jet

Thermal barrier—C-6 (0.26" dia.; less dense braid):

- Sustains 2900-3000 °F for 20 sec (2x joint cavity fill time)
- Causes a large temperature drop of 2500-2900 °F (T_{hot} - $T_{cold\ bulk}$)

Temperature 1/4-in. downstream stays within Viton O-ring temperature limit

CD-99-79226

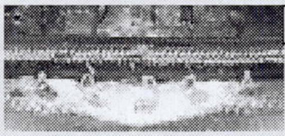
This chart shows the results of temperature drop tests performed on the 0.26” diameter C-6 thermal barrier. The plot on the left shows temperature traces recorded for a 20 to 25 second torch exposure. Temperature traces for the center thermocouples and those to the right of center on both the upstream and downstream sides of the thermal barrier are shown in degrees Fahrenheit. Thermocouple readings to the left of center were symmetric to those to the right of center and are not shown here for clarity. One can see that the center thermocouple on the hot side reached about 3200°F and that the temperature readings decreased for the thermocouples farther from center. The center thermocouple on the cold side reached about 1200°F with temperatures dropping away from center. Even after a 20 to 25 second torch exposure, the temperature 1/4" downstream of the thermal barrier barely reached 500°F, well within the Viton O-ring temperature limit.

The plot on the right shows the temperature difference between the center thermocouple on the hot side and the cold bulk temperature. A large temperature drop of 2500 to 2900°F was observed during this test.

Thermal Barrier Condition vs. Accumulated Time

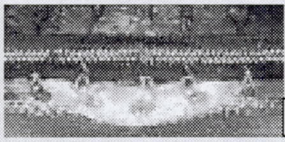
C-3 Thermal Barrier

C-6 Thermal barrier

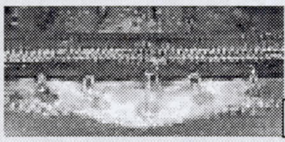


Test # 30

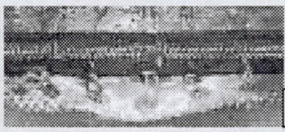
Test #	Exposure Time		T_{hot} @ 15 sec (deg F)	T_{bulk} @ 15 sec (deg F)	T_{hot}-T_{bulk} @ 15 sec (deg F)
	Per test (sec)	Accumulated (sec)			
30	30	30	3070	210	2860
31	30	60	3050	230	2820
32	60	120	3020	200	2820
33	60	180	2590	150	2440



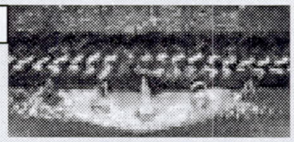
Test # 31



Test # 32



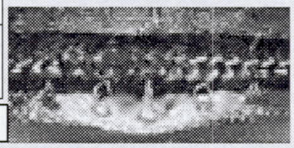
Test # 33



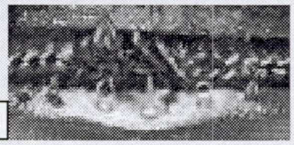
Test # 35

Test # 36

Test #	Exposure Time		T_{hot} @ 15 sec (deg F)	T_{bulk} @ 15 sec (deg F)	T_{hot}-T_{bulk} @ 15 sec (deg F)
	Per test (sec)	Accumulated (sec)			
35	30	50	2730	170	2560
36	30	80	2690	190	2500
37	60	140	2520	280	2240
38	60	200	2700	280	2420



Test # 37



Test # 38

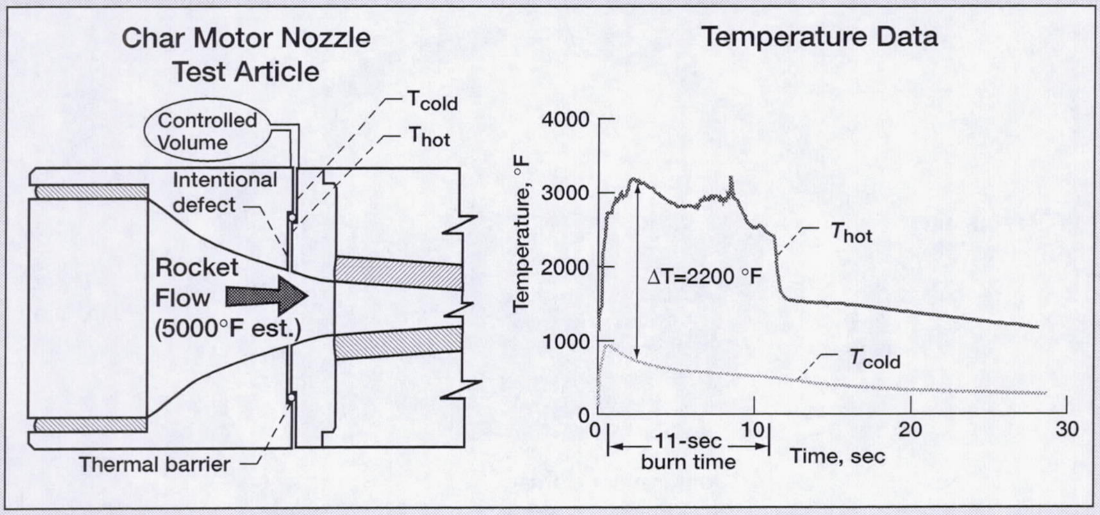
- C-3 and C-6 sustained 2500-3000 °F for 60 second intervals (180-200 sec accumulated time) with little damage. C-3: 0.029-in. recession; C-6: 0.092-in. recession.

No evidence of hot gas path around thermal barrier

CD-99-79413

This chart shows the results of repeated torch exposures on one C-6 specimen. The four photos on the right side show the condition of the specimen after two torch exposures of 30 seconds and two exposures of 60 seconds for a total of over three minutes of torch exposure. There was some minor damage to the specimen by the end of the fourth test, but the majority of the cross section was still intact, and there were no signs of hot gas paths around the specimen. This series of tests was much longer and more extreme than what the thermal barrier would be exposed to in the solid rocket motor.

Thiokol Char Motor Test Results: C-6 Thermal Barrier

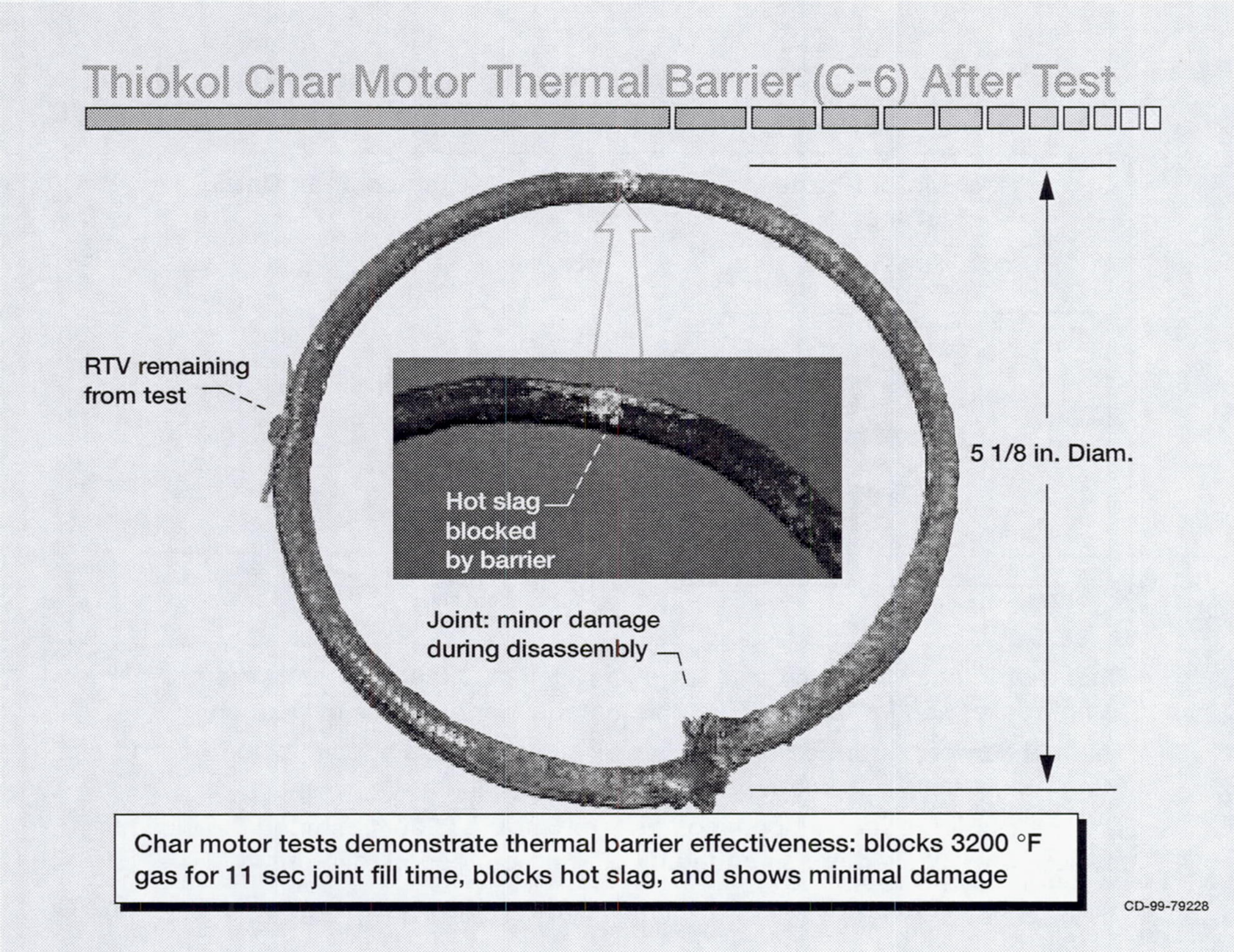


- **Char motor test with intentional large joint defect (0.060") subjects thermal barrier to hot rocket gas for temperature and material performance evaluation**
- **Thermal barrier performed extremely well subjected to hot gas (3200 °F) for 11 sec firing – simulating maximum downstream cavity fill time**
- **Thermal barrier reduced incoming gas temperature 2200 °F, spread the incoming jet-flow, and blocked hot slag thereby offering protection to O-rings**

Thermal barrier: C-6, 0.26" diameter

CD-99-78855a

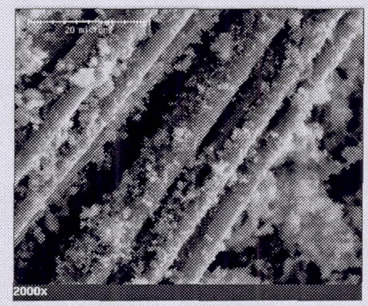
Thiokol has performed a series of tests in a subscale rocket "char motor" in which the thermal barrier was exposed to hot rocket gases. The figure on the left shows the test setup in which hot gases passed through an intentional 0.06" wide joint defect and impinged on the thermal barrier before filling a controlled downstream volume. Pressures and temperatures were measured both upstream and downstream of the thermal barrier. The plot on the right shows temperature traces from a test performed on a 0.26" diameter C-6 thermal barrier specimen in the char motor. The thermal barrier performed extremely well while withstanding hot side temperatures of 3200°F for an eleven-second rocket firing. It dropped the temperature by 2200°F across its diameter, spread the incoming hot gas flow, and blocked hot slag. When the specimen was removed from the char motor, it was in excellent condition with no apparent burning or charring. These test results were consistent with the results from our temperature drop tests in which we measured 2500+°F drops across the same C-6 thermal barrier design.



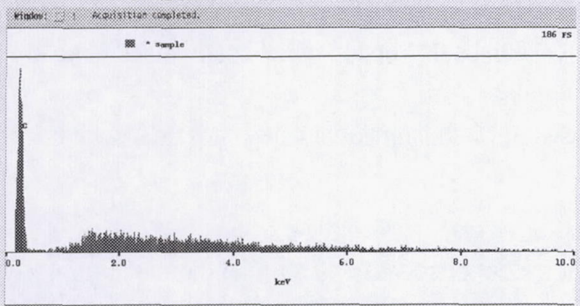
This is a photograph of the specimen that Thiokol tested in the char motor in the previous chart. The specimen was in very good condition with only minor damage at the splice joint caused during disassembly. There were no signs of burning or charring of the specimen, but deposits could clearly be seen both on and between the carbon fibers.

NASA GRC Examination of Thermal Barrier from Char Motor Test

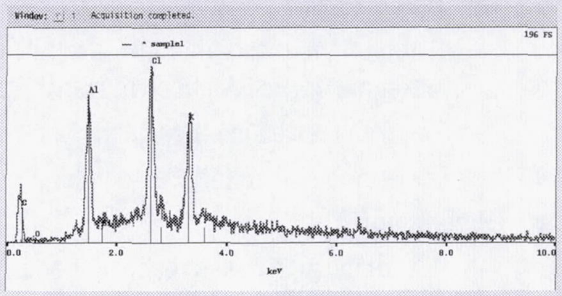
- **Observations**
  - Chemical analysis of as-received thermal barrier showed only carbon present
  - Chemical analysis of char motor specimen revealed presence of: aluminum, silicon, chlorine, potassium, and carbon
  - Potential sources: Aluminum: Rocket fuel;
    Silicon: Chopped silica phenolic insulation blocks;
    Chlorine: Ammonium perchlorate oxidizer;
    Potassium: Unknown



SEM Photo of Upstream Side of Thermal Barrier (2000X)



Chemical Analysis of As-Received Thermal Barrier



Chemical Analysis of Thermal Barrier After Char Motor Test (2000X)

To further examine the thermal barrier specimen that was tested in the Thiokol char motor, we sectioned the specimen and examined it in a scanning electron microscope. The image at the upper right shows that there was no damage to individual carbon fibers within the specimen. The fibers were still cylindrical and relatively smooth. The thermal barrier did act as an effective slag barrier, though, filtering out particles and trapping them on and between the carbon fibers. To analyze the deposits even further, a chemical analysis was performed on them. At the bottom left of this chart is a chemical analysis of an as-received specimen that had not been tested in the char motor. As would be expected, the only peak that showed up was for carbon, since there were very few other deposits or impurities in the specimen. At the lower right is the plot of the chemical analysis performed on the specimen that was tested in the char motor. This test revealed the presence of aluminum, silicon, chlorine, and potassium in addition to carbon. Through discussions with Thiokol, the presence of all of these species was explained. The aluminum came from the solid fuel used in the rocket. The silicon most likely was deposited on the specimen as the chopped silica phenolic insulation blocks around the specimen became charred. The chlorine came from the ammonium perchlorate oxidizer, and the potassium came from the igniter used to fire the rocket.

NASA GRC Thermal Barrier Feasibility Proven in MNASA-10 RSRM

- **<u>Test Parameters</u>**
  - Carbon-6 thermal barrier tested in MNASA-10 1/5th-scale version of full-scale reusable solid rocket motor (RSRM) used to launch space shuttle
  - Specimen tested in redesigned nozzle-to-case joint with intentional flaw in nozzle insulation
  - Rocket motor fired for 29 seconds
- **<u>Observations</u>**
  - Hot combustion gases reached thermal barrier: Soot observed upstream of thermal barrier
  - No soot downstream
  - No damage or erosion to thermal barrier or downstream O-rings

On August 10, 1999, the Carbon-6 thermal barrier was tested in an MNASA-10 1/5th-scale version of the full-scale solid rocket motors used to launch the Space Shuttle. Tested in a redesigned nozzle-to-case joint for a 29 second rocket firing, an intentional flaw in the nozzle insulation allowed hot combustion gases to reach the thermal barrier as evidenced by soot observed on hardware upstream of the thermal barrier. Post-test inspection revealed no soot downstream of the thermal barrier and no damage or erosion to either the thermal barrier or to downstream O-rings that the thermal barrier is designed to protect. The results of this test demonstrated that the thermal barrier is capable of protecting downstream O-rings from hot rocket gases in large-scale solid rocket motors.

Summary and Conclusions

NASA Glenn thermal barriers resist 5500°F flame for greater than 6 minutes before burn-through:

- **Expected joint cavity fill time ≤ 10 sec.**
- **Anticipated mass-loss mechanism: Carbon oxidation**

Braided thermal barriers:

- **Permit gas flow to fill joint cavity and cause a large (2200 °F and above) temperature drop through diameter**
- **Spread flame preventing pass-through of damaging focused jet**
- **Protect downstream Viton O-ring: gas temperatures 1/4-in. downstream of barrier are within Viton O-ring temperature limit**
- **Exhibit adequate resilience to accommodate joint movement**

CD-98-78004b

In summary, the NASA Glenn thermal barrier has demonstrated the ability to resist the 5500°F flame of an oxy-acetylene torch for over six minutes before being cut through. This is much longer than the expected nozzle-to-case joint cavity fill time of less than ten seconds that it would have to endure in the solid rocket motors. It is believed that the actual mass-loss mechanism involved in this process is oxidation of the carbon fibers that make up the thermal barrier. The thermal barrier is permeable enough to permit gas to flow through it to fill the downstream joint cavity while at the same time causing a large (2200+°F) temperature drop across its diameter. It protects downstream Viton O-rings by spreading focussed hot gas jets and lowering gas temperatures to within the Viton temperature limit. The thermal barrier also exhibits adequate resiliency to accommodate joint movements.

Summary and Conclusions (Concluded)

Thiokol Char Motor Results

- Thermal barrier performed extremely well subjected to hot gas (3200 °F) for 11 sec firing—simulating maximum downstream joint cavity fill time
- Thermal barrier reduced incoming gas temperature 2200 °F, spread incoming jet-flow, and blocked hot slag thereby offering protection to O-rings.

Thermal barrier feasibility established qualifying it for comprehensive evaluation

CD-98-78004c

Results of char motor tests that Thiokol conducted showed that the thermal barrier performed extremely well when subjected to 3200°F hot gases for an eleven second rocket firing. It reduced the incoming hot gas temperature by 2200°F, spread incoming gas jets, and blocked hot slag to protect the downstream O-rings. Results of the most recent MNASA rocket tests on the thermal barrier showed that it blocked soot with no damage to either the thermal barrier or the downstream O-rings. All of these positive results have qualified the thermal barrier for further testing and evaluation to qualify it for use in the nozzle-to-case joint and Joint 2 of the Shuttle solid rocket motors.

Planned Future Work

- **NASA Glenn:** Evaluate performance characteristics of future generation thermal barriers
- **Thiokol:** Further evaluate thermal barrier performance in char motor and other joint simulation tests.
- **Thiokol/NASA Marshall:** Perform full-scale solid rocket motor tests with NASA Glenn designed thermal barriers

Schedule

- Redesigned joint, Nominal	Jan, 2001
- Redesigned joint, with flaw	May, 2002
- First shuttle flight	Sept, 2002

CD-98-77569a

Thiokol's current test plan will culminate with testing of the thermal barrier in full-scale solid rocket motor tests of the redesigned joint in January 2001 (nominal condition, without flaw) and in May 2002 (with flaw). This all leads up to an anticipated first Shuttle flight using the thermal barrier in September 2002.

BRAIDING FUNDAMENTALS AND SEAL FABRICATION AT ALBANY-TECHNIWEAVE

Bruce Bond
Albany International Techniweave, Inc.
Rochester, New Hampshire

Albany International Techniweave, Inc

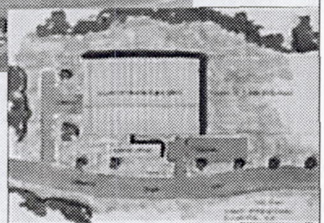
- Techniweave was acquired by Albany in 1998
- Albany's sales exceed 850 Million Dollars/year
- Fabricating High Temperature seals since 1991
- Techniweave will have a new facility in 90 days

Albany International Techniweave

TECHNIWEAVE

Albany International is the world's leading suppliers of Paper Machinery Clothing. Albany acquired Techniweave in March of 1998 and combined it with the Engineered Products Group of the Albany International Research Company (AIRESCO), Mansfield Massachusetts. The combined organization is known as Albany International Techniweave, Inc.. Techniweave and the Engineered Products Group provided products and services to many of the same customers and were viewed as complimentary businesses.

New Facility



–4th quarter '99 scheduled completion
–co-locate personnel and equipment from our current Rochester, NH and Mansfield, MA operations
–located in Rochester, NH within 5 miles of existing facility
–4800 sq. ft. office area / 60,000 sq. ft. manufacturing area
–site preparation to accommodate future 60,000 sq. ft. expansion of manufacturing area as business requires

Albany International Techniweave

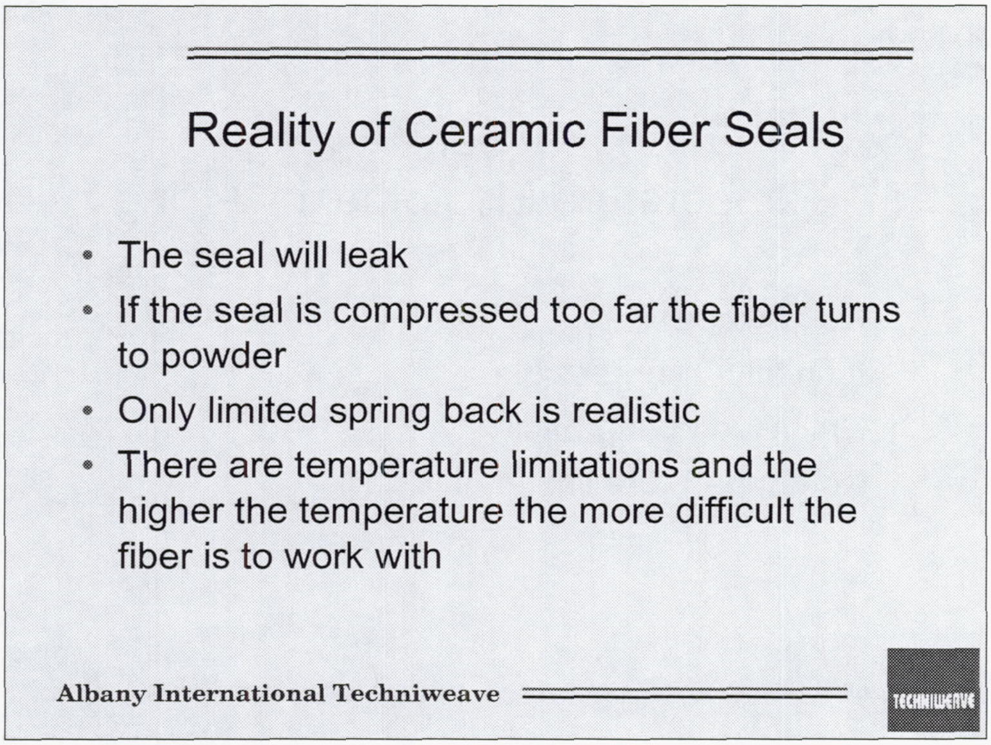
This facility will be the new home of Albany International Techniweave Inc. It is anticipated that all equipment and personnel will be relocated in January of 2000. The site allows for the expansion of the base building on an incremental basis as needed.

The Ideal Seal…A High Temperature Elastomeric O-Ring

- No leakage
- Infinitely compressible
- Unlimited spring back
- No temperature limitation

Albany International Techniweave

The ideal high temperature seal would have the same properties as an elastomeric O-ring but without the temperature limitations.



The reality of high temperature seals is often far from the ideal. Engineers are forced to find innovative methods for utilizing ceramic seals.

The Raw Materials

- Ceramic fiber yarns
  - Nextel 312
  - Nextel 440
  - Nextel 550
  - Nextel 610
  - Nextel 720
  - Altex

Albany International Techniweave

Ceramic seals can be fabricated from a number of commercially available yarns. The specific yarn choice is guided by the max use temperature and the environment. Typical prices for yarns range from $75 to $750 per pound.

The Raw Materials, cont'd

- High temperature alloy wire
  - Haynes 188
  - Inconel
  - Stainless steel

Albany International Techniweave

Hybrid braids, (ceramic core with metallic sheath) offer increased environmental resistance where vibration and/or air flow past the seal is anticipated

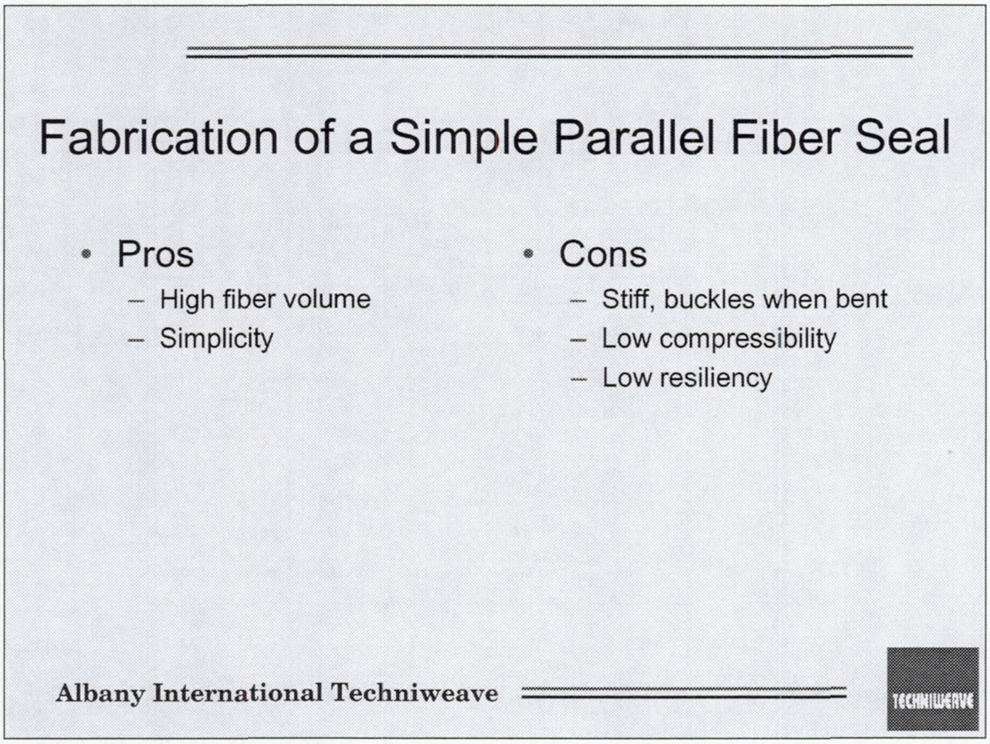
Nextel Ceramic Fiber Typical Properties

Nextel 312, 440, 550, 610 & 720

Property	Units	Nextel 312	Nextel 440	Nextel 550	Nextel 610	Nextel 720
Filament Diameter	μm	10-12	10-12	10-12	10-12	10-12
Crystal Type		$9Al_2O_3$: $2B_2O_3$ + amorph. SiO_2	gamma Al_2O_3 + mullite + amorph. SiO_2	gamma Al_2O_3 + amorph. SiO_2	alpha Al_2O_3	alpha Al_2O_3 + mullite
Density	g/cm³	2.70	3.05	3.03	3.88	3.40
Filament Tensile Strength (25,4mm gauge)	Mpa ksi	1700 250	2000 290	2000 290	2930 425	2100 300
Filament Tensile Modulus	Gpa msi	150 22	190 27	193 28	373 54	260 38
Chemical Composition	wt%	62 Al_2O_3 24 SiO_2 14 B_2O_3	70 Al_2O_3 28 SiO_2 2 B_2O_3	73 Al_2O_3 27 SiO_2	>99 Al_2O_3	85 Al_2O_3 15 SiO_2
Allowable Yield Variation	yds/lb.	specified ± 10%	specified ± 10%	specified ± 10%	specified ± 10%	specified ± 10%

Albany International Techniweave

The data included here is copied form the 3M Nextel data handbook. The yield of the incoming material is indicated as +/- 10%. This potential variability presents special challenges to the fabricator and the end user.



Some of the earliest seals were fabricated by over-wrapping an inner core of parallel fibers. This construction is still favored for some specific applications. The seal has relatively low leakage but lacks flexibility and resiliency.

Braided Seal Fabrication

- Pros
  - Flexible
  - Tailorable
    - Size
    - Permeability
    - *Resiliency*
  - Resistance to wear
  - *Diameters from .05" to .5"*
- Cons
  - Requires more labor

Albany International Techniweave

Braided seals consist of a minimal core with layer over layer of braided ceramic fibers. The characteristics of the seal can be tailored to fit the specific application. The multiple layers increase the labor costs significantly. However, the resulting seals are conformable and can be provided in a wide range of materials and architectures.

Braid Descriptors

- Number of carriers
- Braider configuration
- Yarn base material
- Yarn ply and twist
- Diameter of material to be braided
- Plaits per Inch
- Tension

Albany International Techniweave

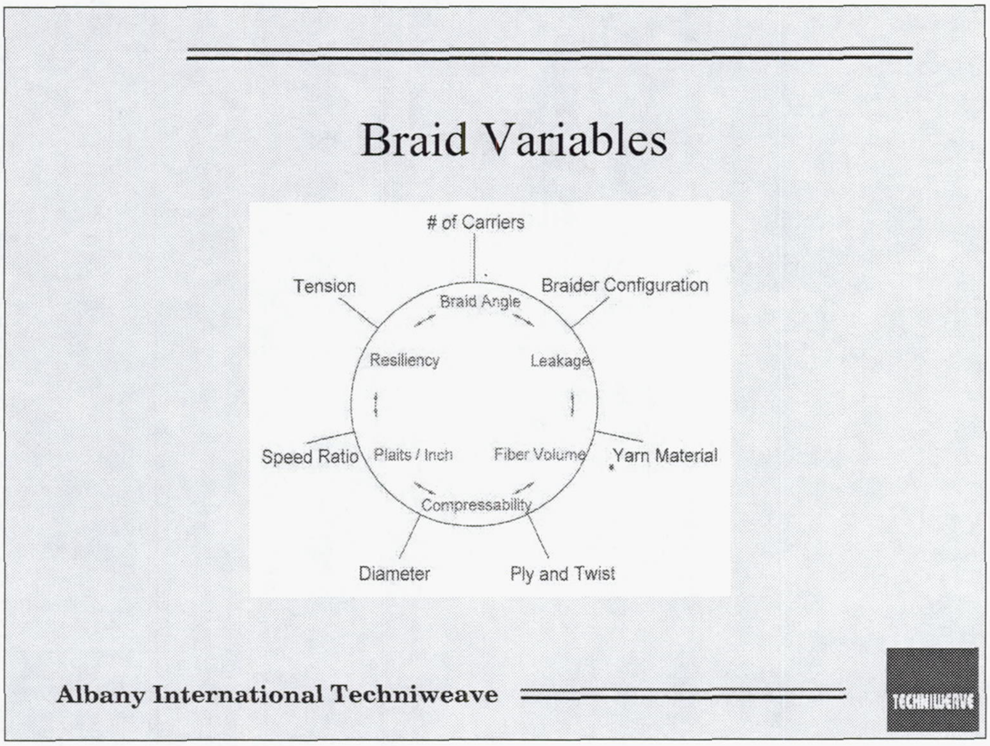
These descriptive terms are used to provide a definition of the braid and its architecture. Each layer in a seal would have is own description.

Seal Descriptors

- Diameter
- Materials of construction
- Compressibility
- Resiliency
- Fiber volume
- Leakage

Albany International Techniweave

A finished seal can be described the these characteristics.



The braiding parameters shown in blue can be changed independently of each other and will effect all of the characteristics shown in red. It is impossible to change any of the seal characteristics shown in red without effecting all of them. Thus the fabrication of a textile braid differs greatly from other manufacturing processes. The braid is a study in equilibriums, where all of the properties are interactive and cannot be held constant while changing only one variable.

HIGH TEMPERATURE SOLID LUBRICANT DEVELOPMENTS FOR SEAL APPLICATIONS

Christopher DellaCorte
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio

Oil-Free Turbomachinery Program

High Temperature Solid Lubricant Developments for Seal Applications

By

Dr. Christopher DellaCorte
NASA Glenn Research Center
Cleveland, Ohio

NASA/CP—2000-210472/VOL1

Oil-Free

Turbomachinery

Lewis Research Center

Program

Oil-Free Turbomachinery

. . . "High-speed rotating equipment operating without oil lubricated rotor supports . . . bearings, dampers, seals" . . .

Oil-Free Turbomachinery Program

Motivation/Goal

Realize revolutionary improvements in performance, efficiency and rotating of Aeropropulsion engines

CD-98-77844

Oil-Free Turbomachinery Program

Approach:

Incorporate recent advances in enabling technologies in...

- Foil Air Bearings
- High Temperature Solid Lubricants
- Computational Rotordynamics and Modeling

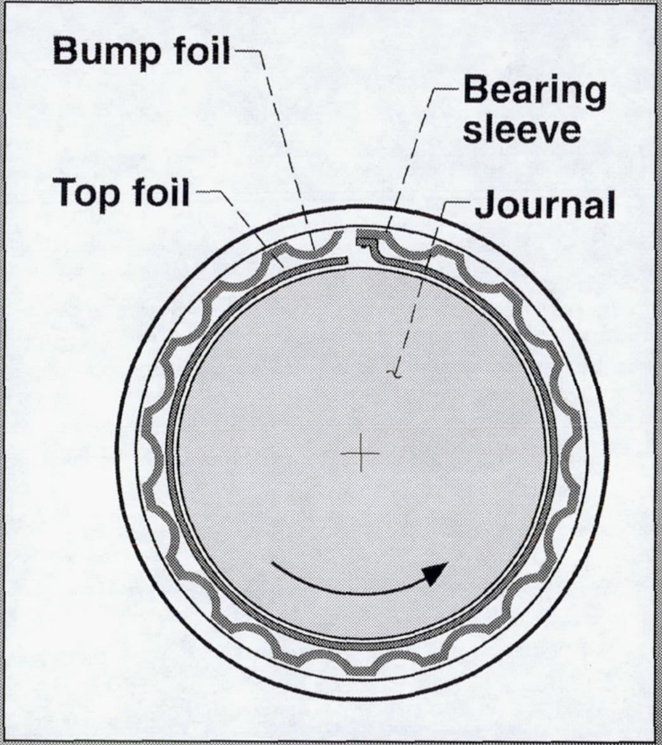
to successfully develop High Speed, High Temperature Oil-free Turbomachinery Systems

CD-98-77845

Oil-Free Turbomachinery Program

Foil Air Bearings...

- Self acting hydrodynamic
- Shaft "floats on air"
- No speed (DN) limit
- Operating temperatures to 1200°F+
- Compliant "spring" bump foil accommodates misalignment



...are ideal for high speed, high temperature applications

...require no maintenance or lubrication system

...exhibit reduced friction and virtually no wear

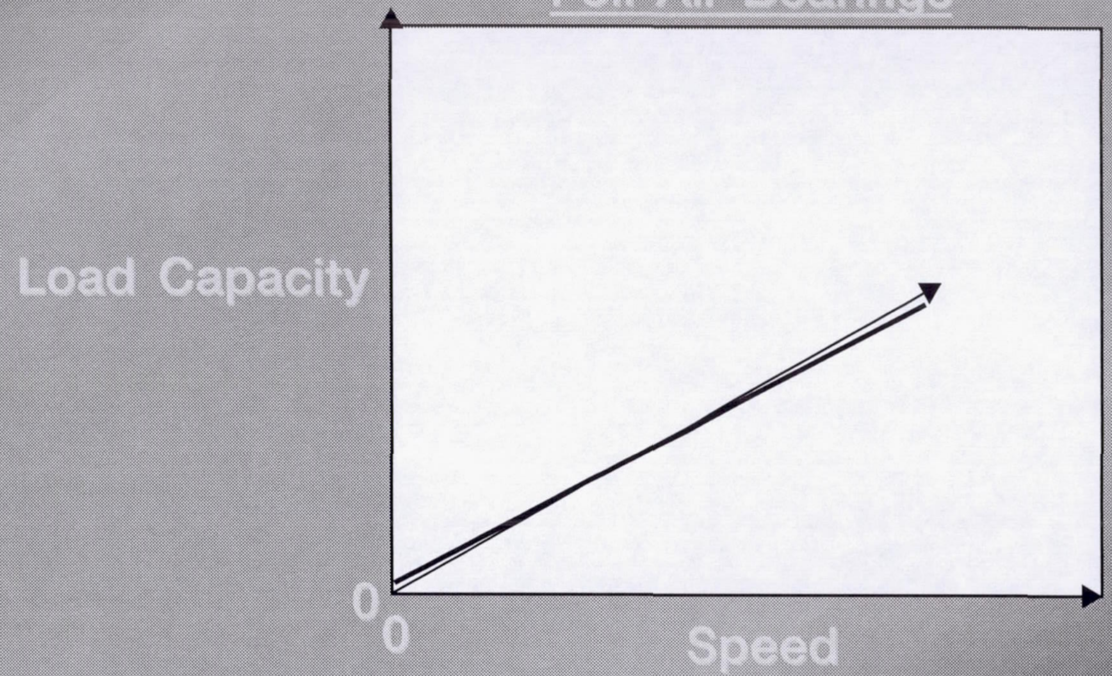
...eliminate possibility of oil related emissions

CD-98-77846

Oil-Free Turbomachinery Program

Bearing Characteristics

Foil Air Bearings



Foil Bearing Load Capacity...is very low at low speeds...
...increases linearly with speed...
...has no practical speed limitation
...requires solid lubricant for start/stop

CD-98-77847

Oil-Free Turbomachinery Program

Current Practice

- Foil surface coated with PTFE or polymide coating
- Shaft coated with Ni or chrome plate
- Limited to 500°F operation
- Alternate "high temperature" solid lubricant (graphite, soft metals) to 800°F due to limited life
- Bearing fails when thin film lubricant worn through to underlying superalloy foil

CD-98-77848

Relevance to Seals

- Sliding which occurs in foil bearings during start-up & shut-down is tribologically similar to certain types of seals (loads, speeds, temperatures)

- Test facilities for foil bearing evaluations are similar to seal conditions

- Environmental durability issues present in foil bearings are also present for seal applications

Oil-Free Turbomachinery Program

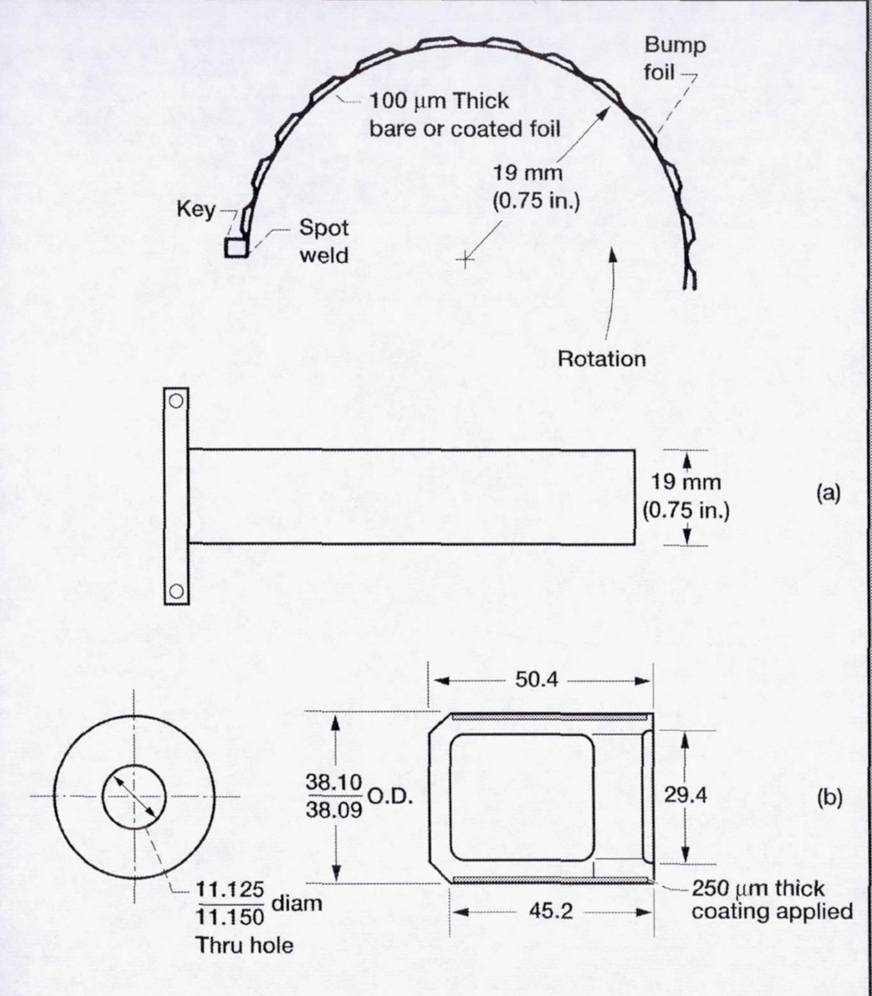
Recent Work

- Coat shaft with thick (250 μm) solid lubricant composite coating (e.g. PS300)
- Conduct start/stop durability tests using partial-arc foil air bearings
- Evaluate results

CD-99-79071

Oil-Free Turbomachinery Program

Test Specimens:



Specimen geometry. (a) Foil. (b) Journal. Units in mm.

Foil: Uncoated Ni Alloy

Journal: PS300

CD-99-79072

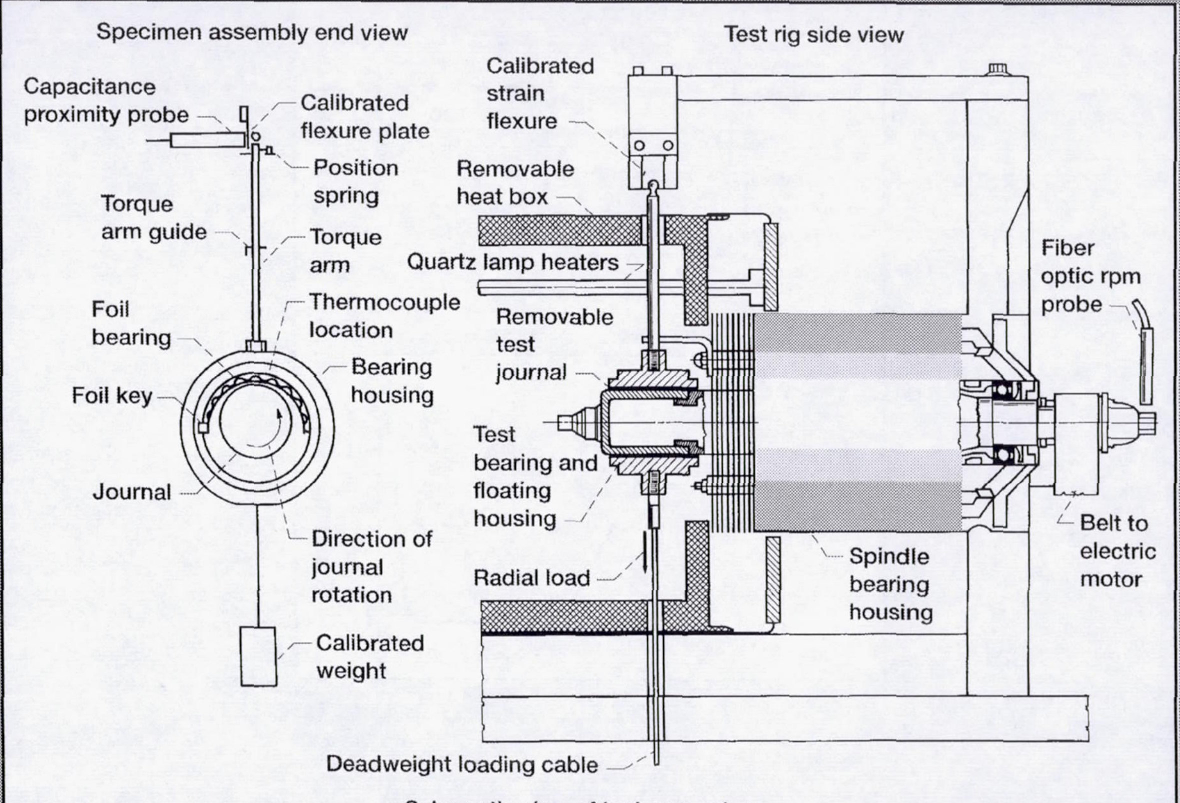
Oil-Free Turbomachinery Program

PS300:	20 NiCr	Binder
	60 Cr_2O_3	Hardener
	10 BaF_2/CaF_2	High-Temp Lube
	10 Ag	Low-Temp Lube

Deposition: Plasma Spray, Carbide grind

CD-99-79073

Testing: High Temperature Foil Bearing Test Rig



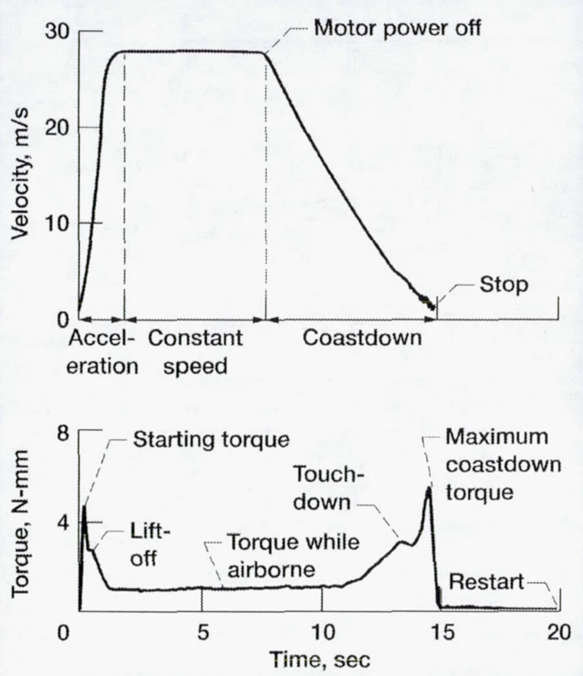
Schematic view of test apparatus.

Conditions: 10.1 KPa (1.5psi), 25 or 500°C, 20,000 start/stop cycles

CD-98-77852

Oil-Free Turbomachinery Program

Test Results:
Sliding occurs at speeds less than 4,000 rpm



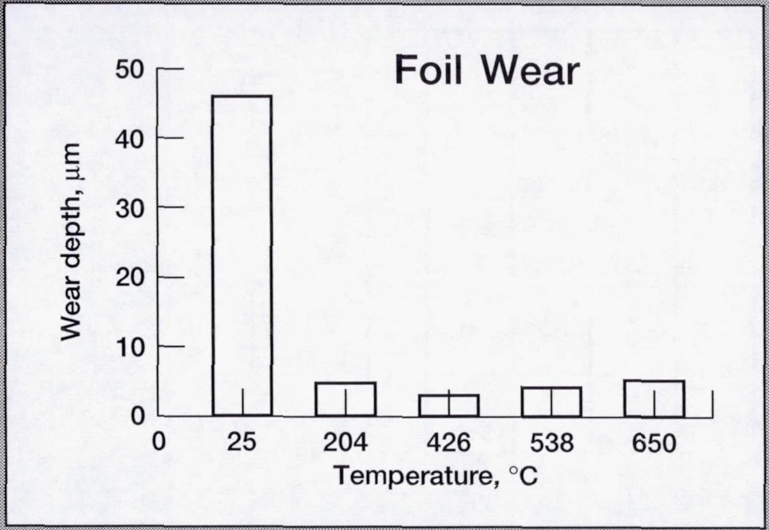
Typical test cycle speed/torque trace.

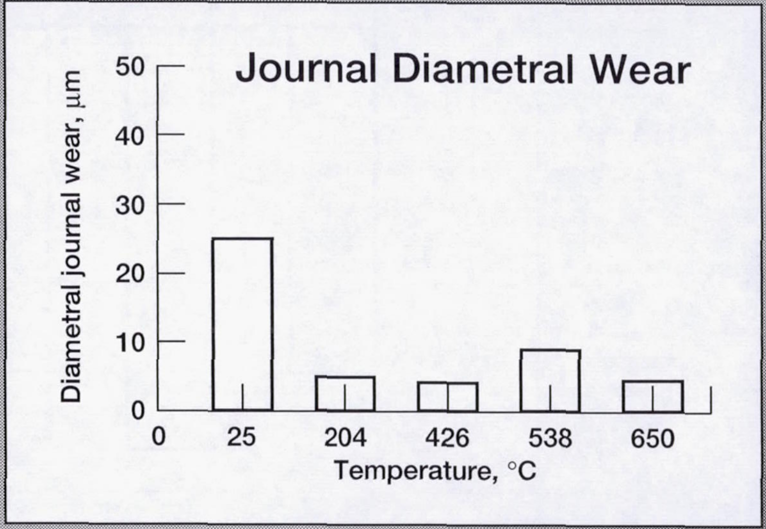
Data:
Torque (friction) measured every 100 cycles
Wear measure every ~ 5,000 cycles

CD-98-77853

Oil-Free Turbomachinery Program

Test Results: Wear





- Wear is highest at 25°C but within order of magnitude.

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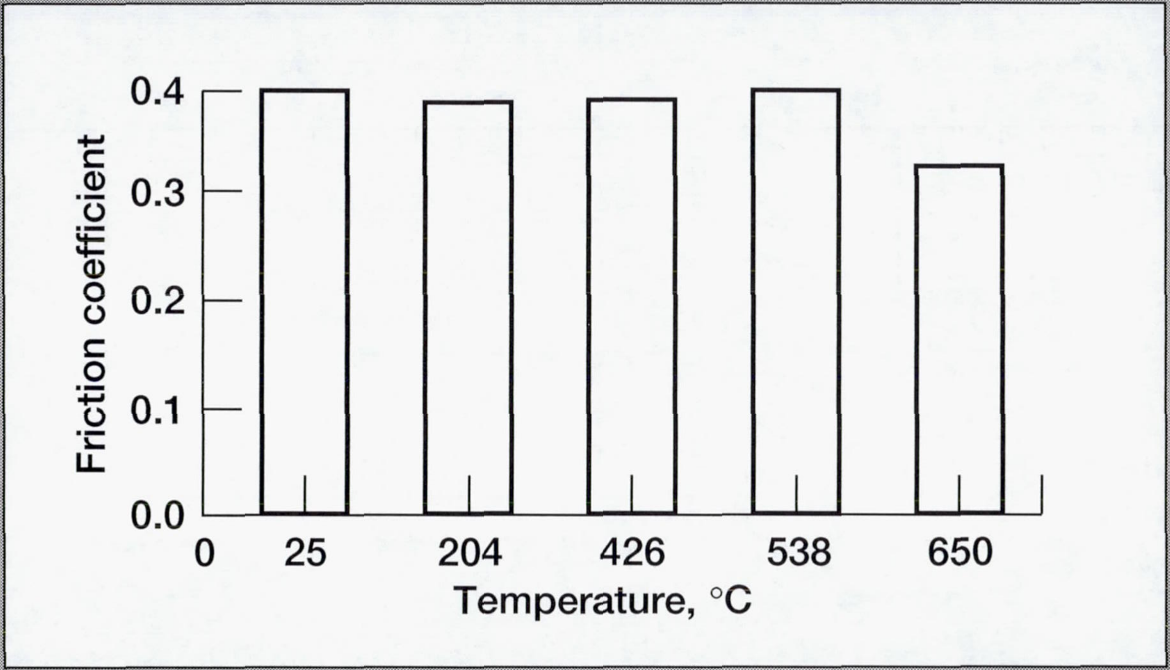
Oil-Free Turbomachinery Program

Test Results: Friction Calculated

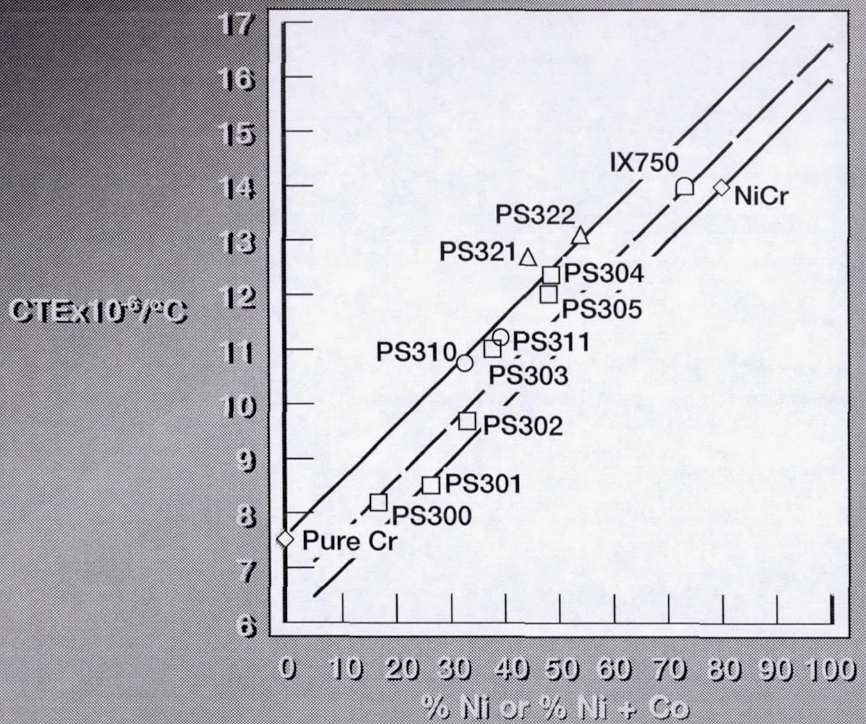


- Friction coefficient is essentially constant with temperature.

CD-99-79079

Oil-Free Turbomachinery Program

PS300 Compositional Tailoring



Constituent	Weight %	
	PS300	PS304
NiCr	60	20
Cr_2O_3	20	60
BaF_2/CaF_2	10	10
Ag	10	10

- PS304 has CTE "match" to superalloy substrates.
- Follow-up pin-on-disk testing of PS304 suggests potential for low friction and lower counterface (foils) wear.

CD-99-79075

Enabling Technology: Coating process development

- Thermal spray technique evaluation
  - Plasma spray
  - HVOF

- Environmental durability
  - 1000's of hours of exposure
  - Microstructural changes
  - Environmental (air vs. inert) effects

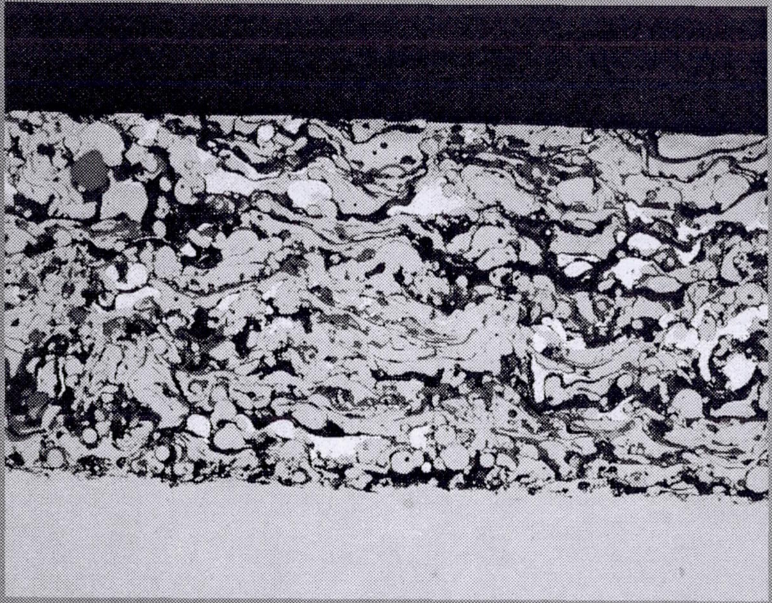
- Coating adhesion enhancement
  - Surface treatment
  - Interfacial binder layers
  - Adhesion testing

Ongoing research efforts anticipate hurdles to overcome them before they are "showstoppers"

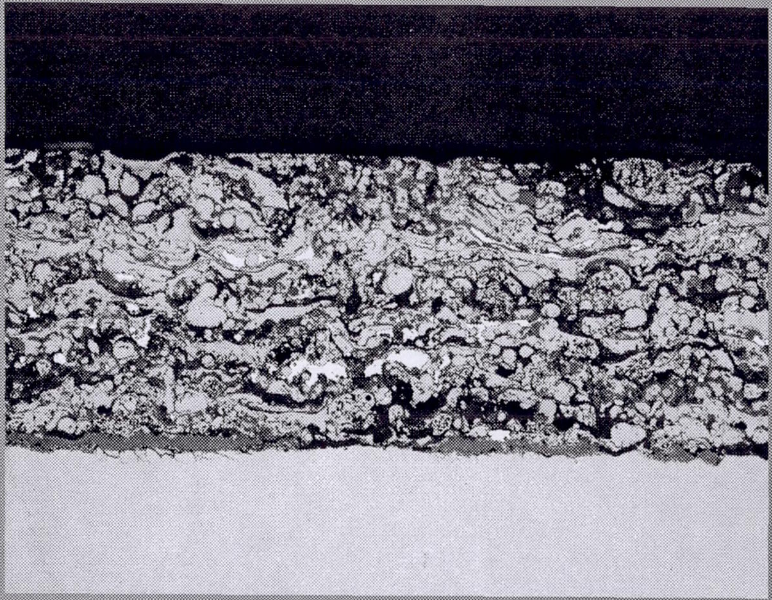
CD-98-77739

Oil-Free Turbomachinery Program

Enabling Technology: Long term coating environmental durability



PS304
As Deposited



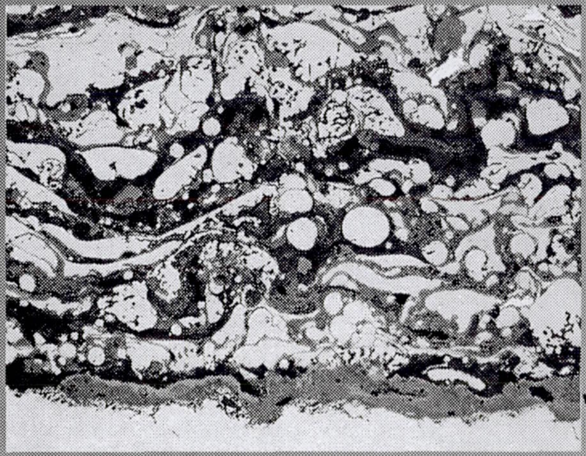
PS304
700 hr at 1200 °F

- Microstructural and interfacial changes observed following long term use at elevated temperatures

CD-98-77741

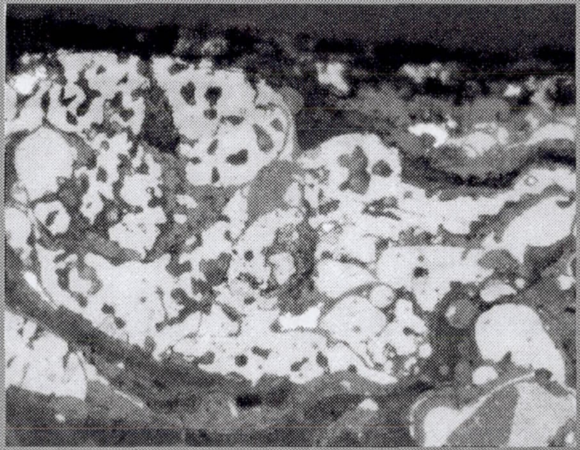
Oil-Free Turbomachinery Program

Enabling Technology: Long term, high temperature effects

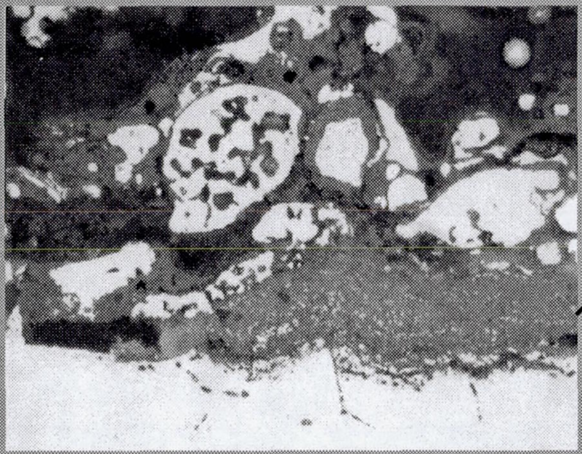


Major Changes

- NiCr binder phase altered



- Interface reaction layer



- Coating and interface changes do not effect performance but are under continued study and development

CD-98-77740

Results Summary

- PS304 reduces friction and wear to manageable levels
- Tirbosurfaces develop smooth, polished characteristics
- PS304 exhibits excellent environmental durability
- PS304 can withstand centrifugal stresses associated with high speed shafts
- PS304 may be a good candidate for intermittent contact seals

NASA GRC CRYOGENIC SEAL TEST RIG CAPABILITY

Margaret Proctor
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio

NASA GRC Cryogenic Seal Test Rig Capability

Presented by
Margaret Proctor

1999 NASA Seal/Secondary Air System Workshop
October 28-29, 1999

NASA Glenn Research Center

Cryogenic Seal Test Rigs at NASA GRC

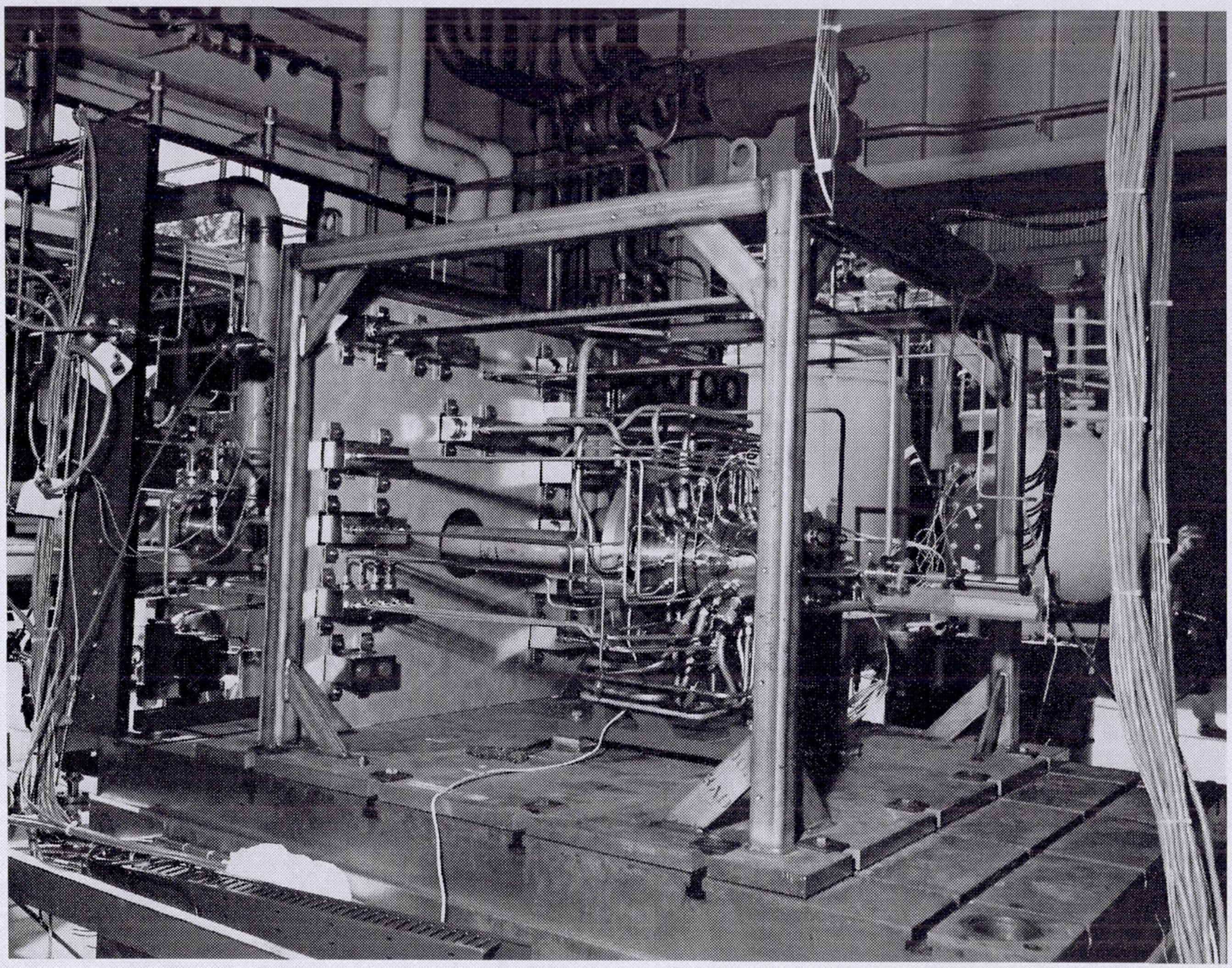
1. LO_x Seal Test Rig

   Designed and built by Mechanical Technology Inc. under NASA Contract NAS3-23260 to test seals for liquid oxygen turbopumps.

2. Cryogenic Brush Seal Test Rig

   - Originally designed and built by Rocketdyne under NASA Contract to test low thrust pumps.
   - Modified by NASA to test brush seals in LN_2 and LH_2.

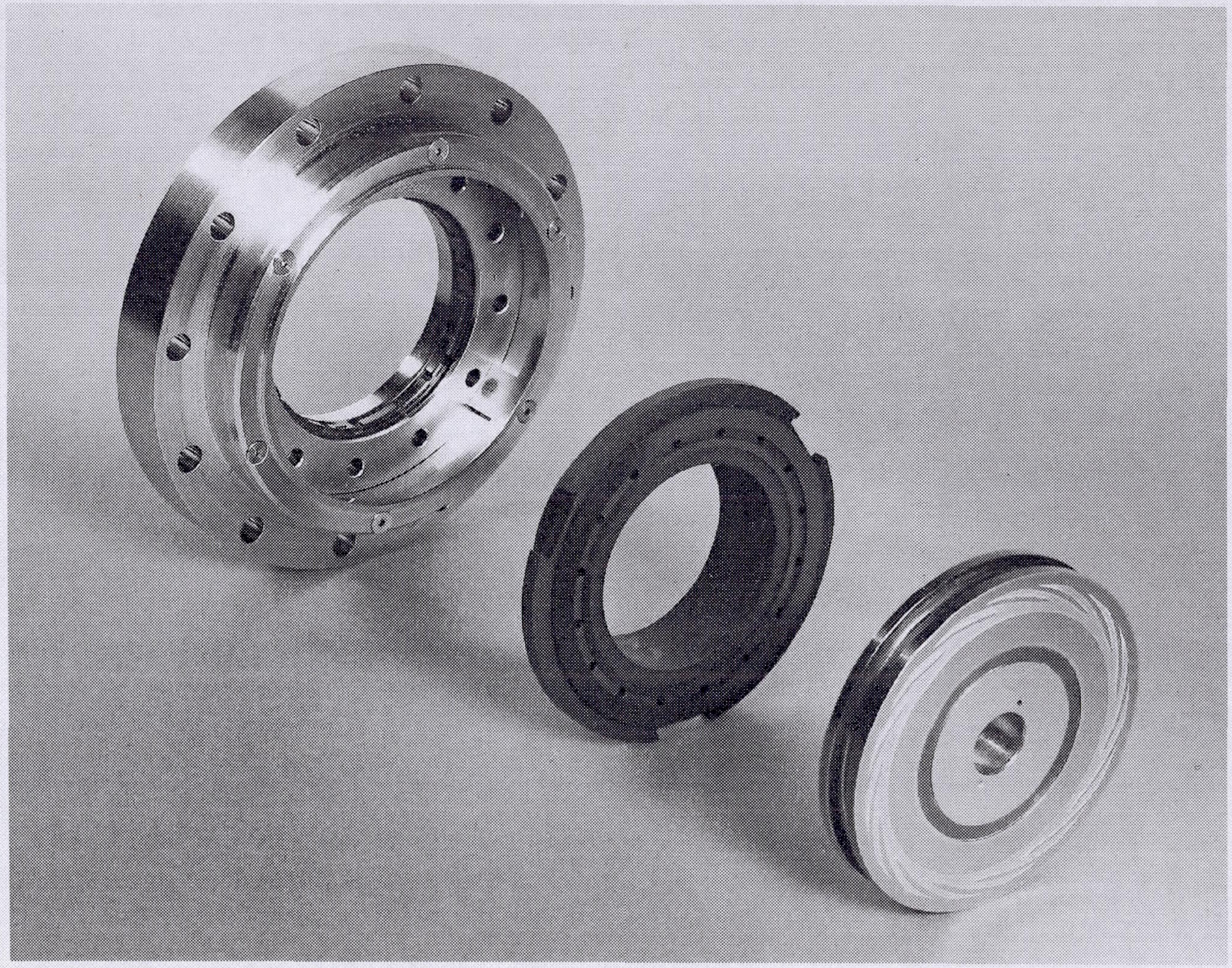
LO_x Seal Test Rig



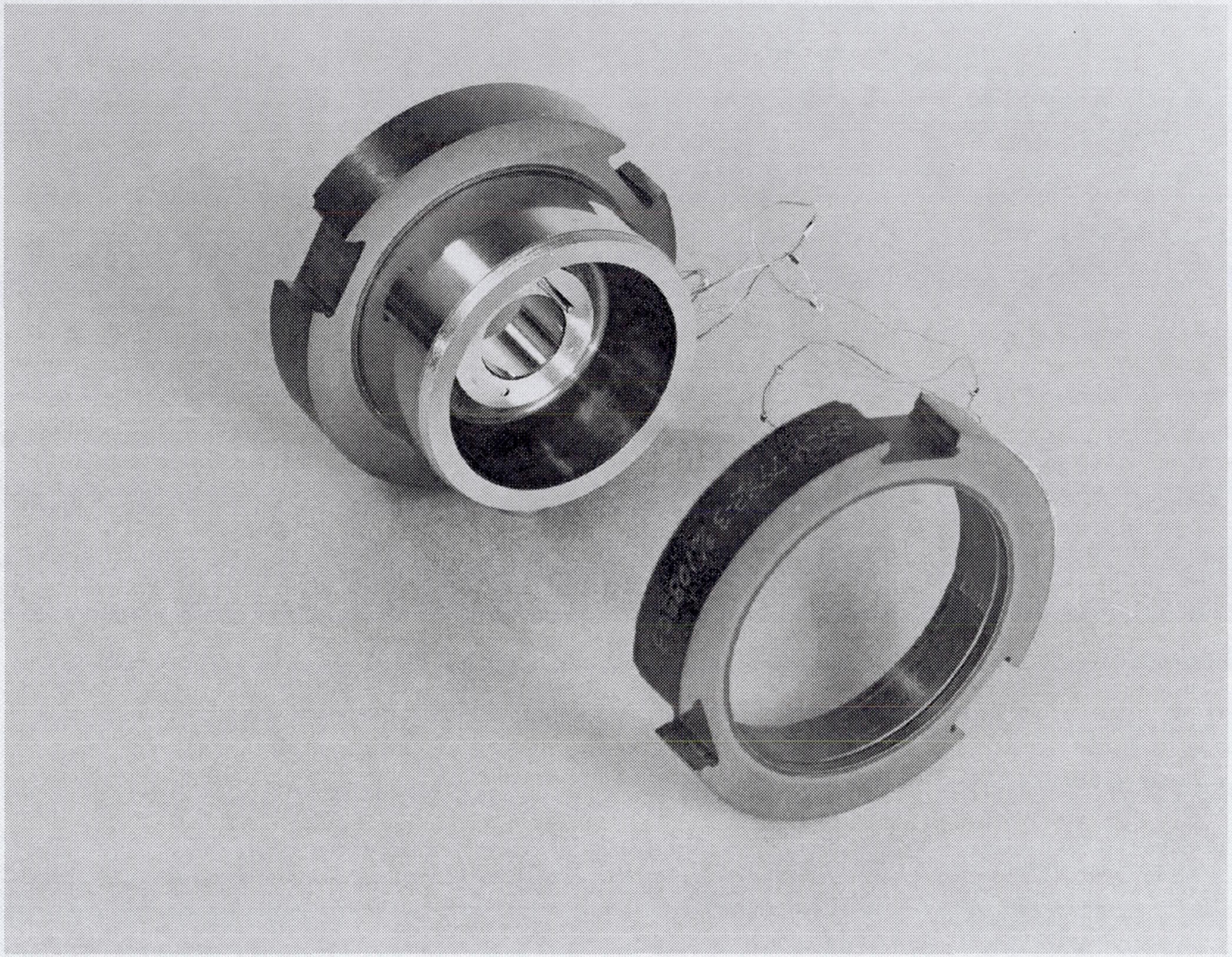
LO_x Seal Test Rig Capabilities

- 50-mm and 20-mm seal hardware
- Face Seal or Ring Seals
- 750 psi LN_2 or LO_X seal supply
- 200 psi GHe seal supply
- 100,000 rpm maximum shaft speed (depending on seal)
- 100 Hp GN_2 turbine drive, overhung, radial in-flow
- Axial vibration can be imposed via thrust bearing control

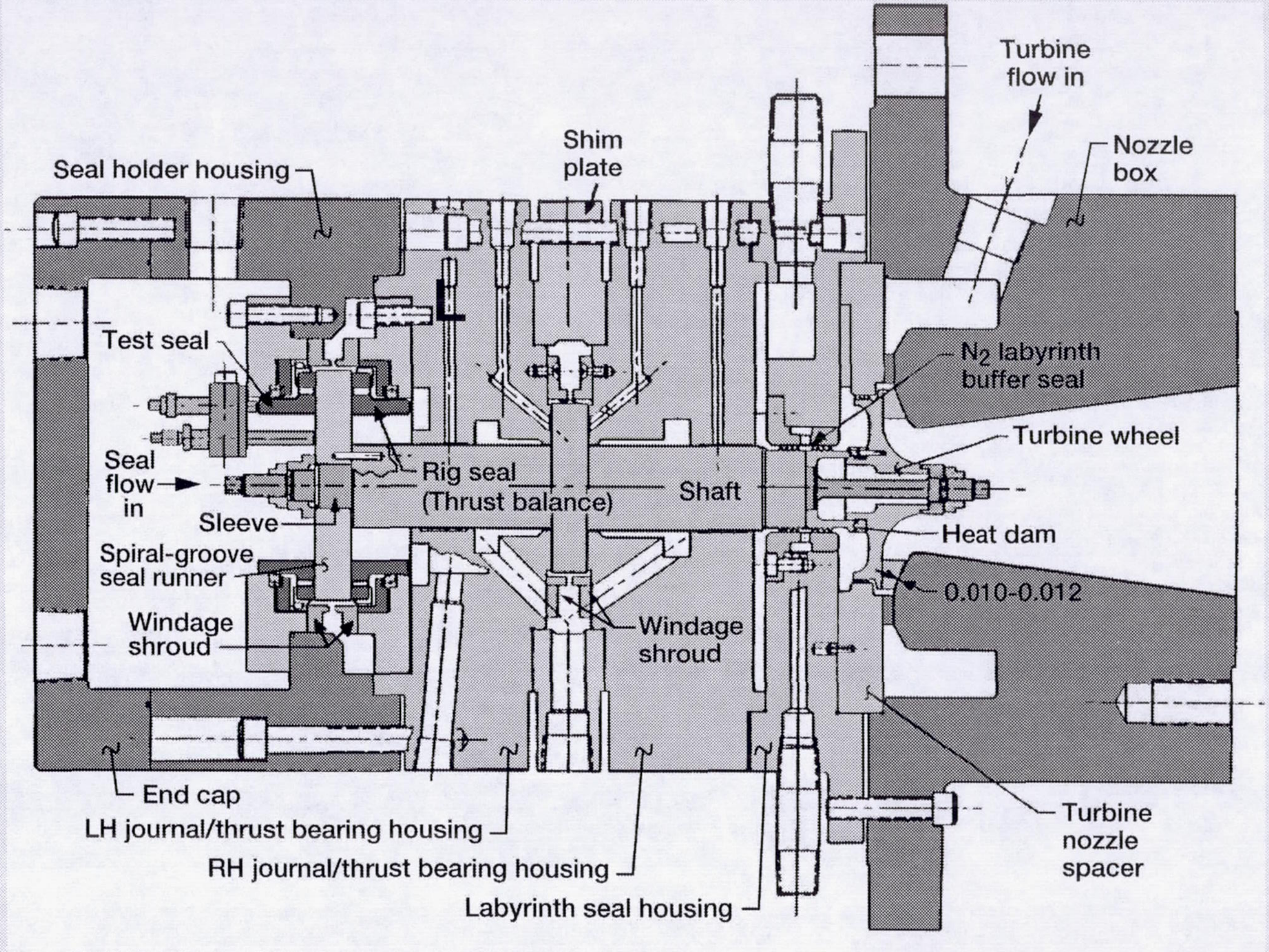
LO_x Spiral Groove Face Seal



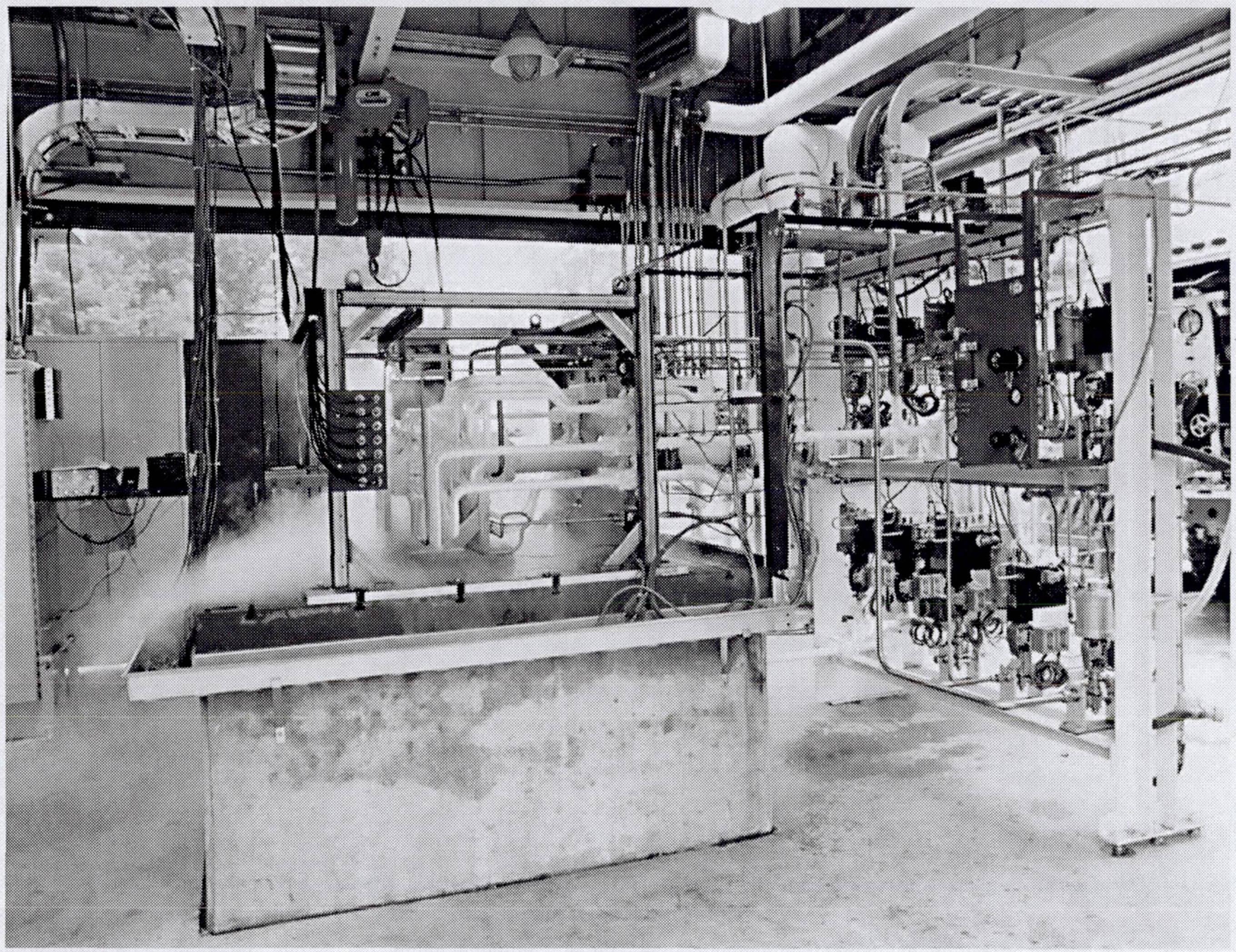
Raleigh-Step Helium Buffer Seal



LO_x Seal Test Rig



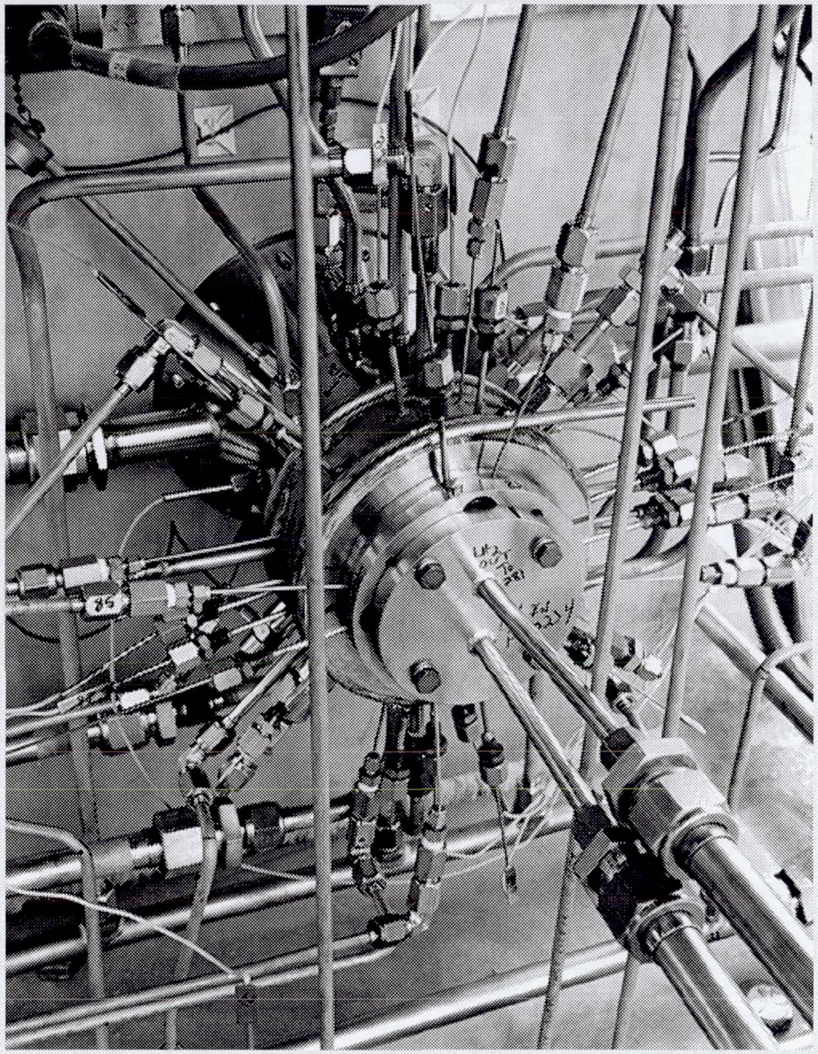
LO$_x$ Seal Test Rig During Test



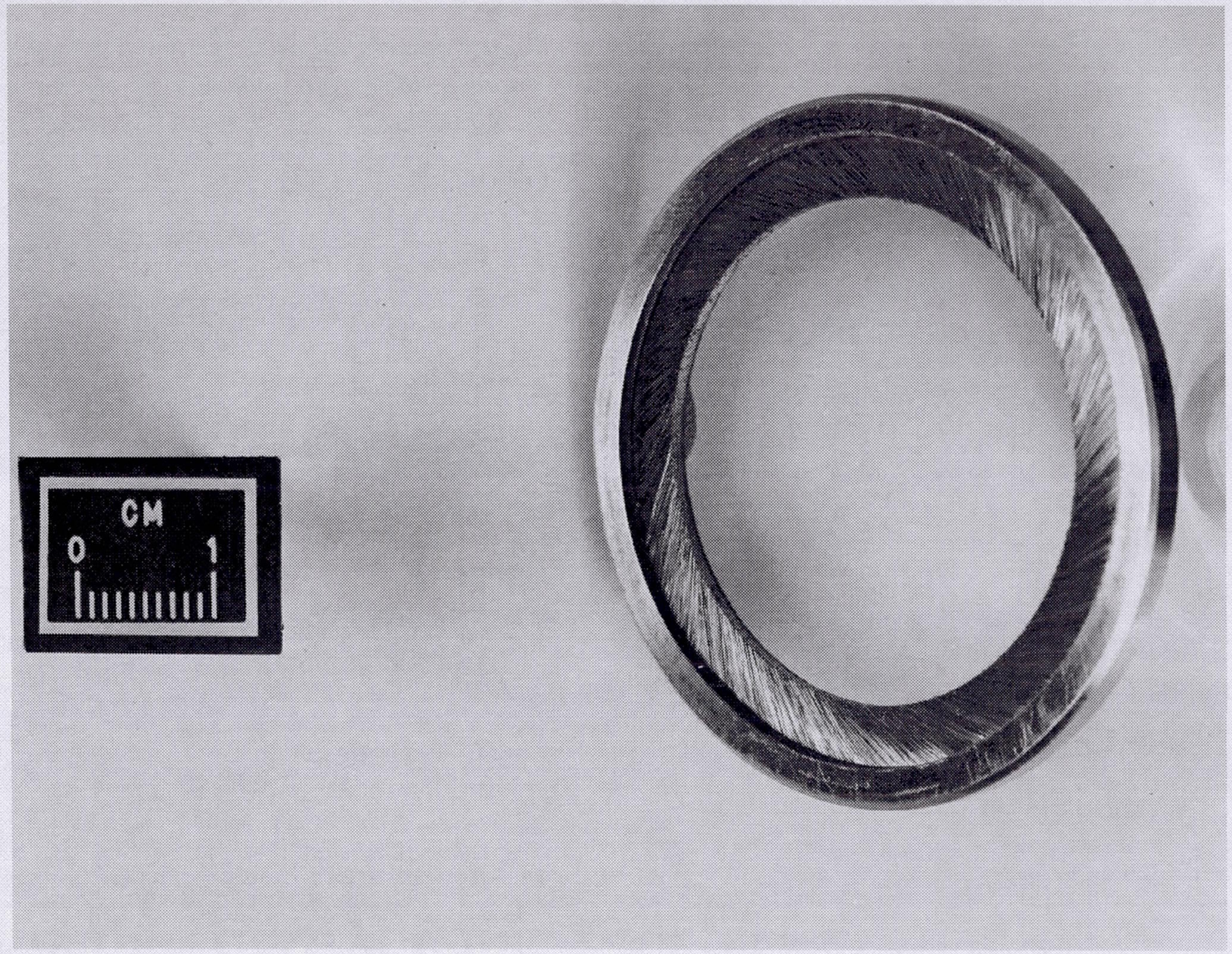
Cryogenic Brush Seal Test Rig Capabilities

- 2 inch diameter bore seals
- 5 brushes at one time - use long, low speed runner
  maximum speed 40,000 rpm
- 1 brush at a time - use short, high speed runner
  maximum speed 65,000 rpm
- 800 psig MAWP of rig
- Maximum Delta-P across seal is 300 psi
  due to balance piston capability
- LH_2 or LN_2
- 14 seal temperature measurement locations
- 14 seal pressure measurement locations
- 3 proximity probes measure rotor orbit

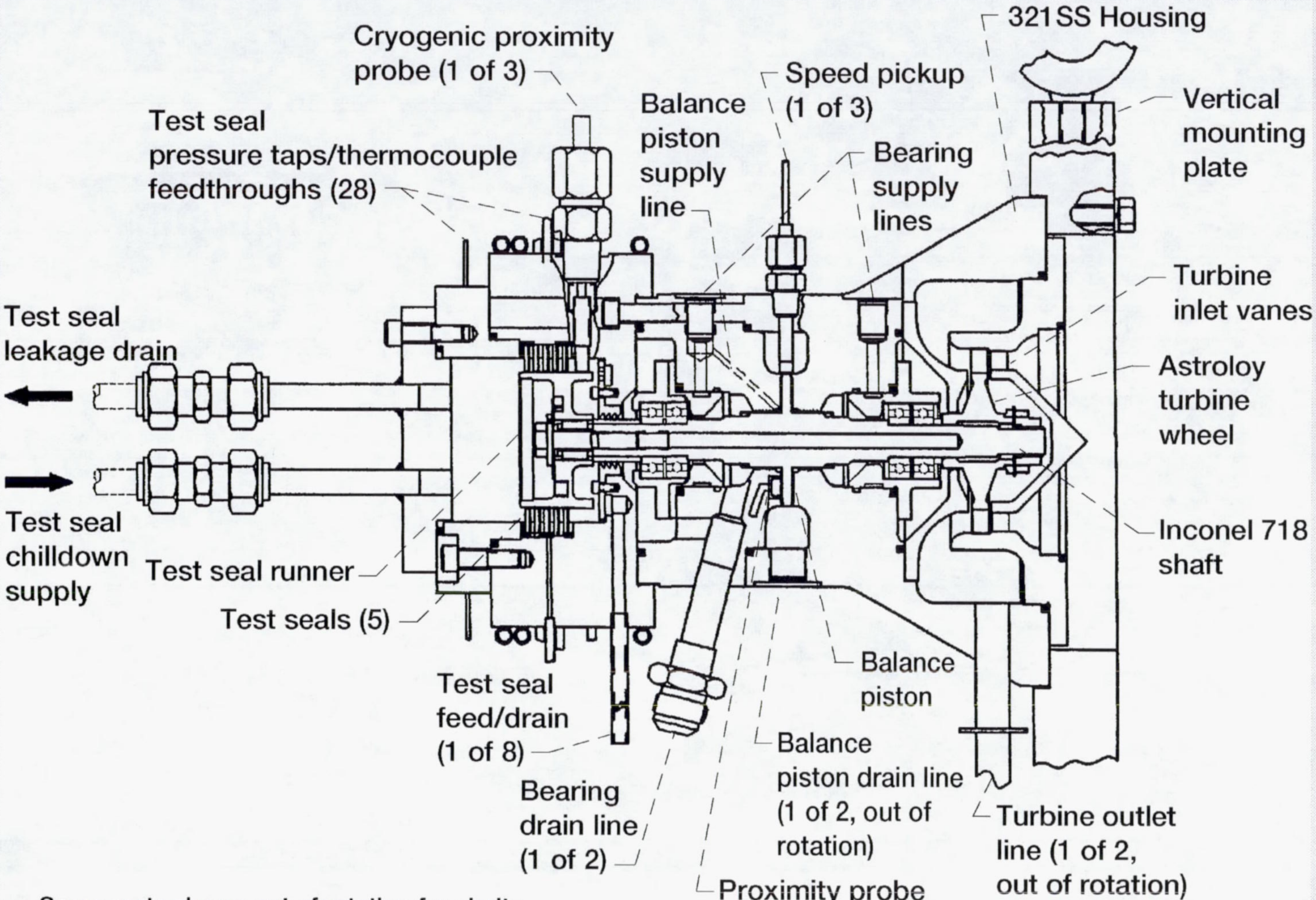
Cryogenic Brush Seal Tester Installation



Typical Brush Seal



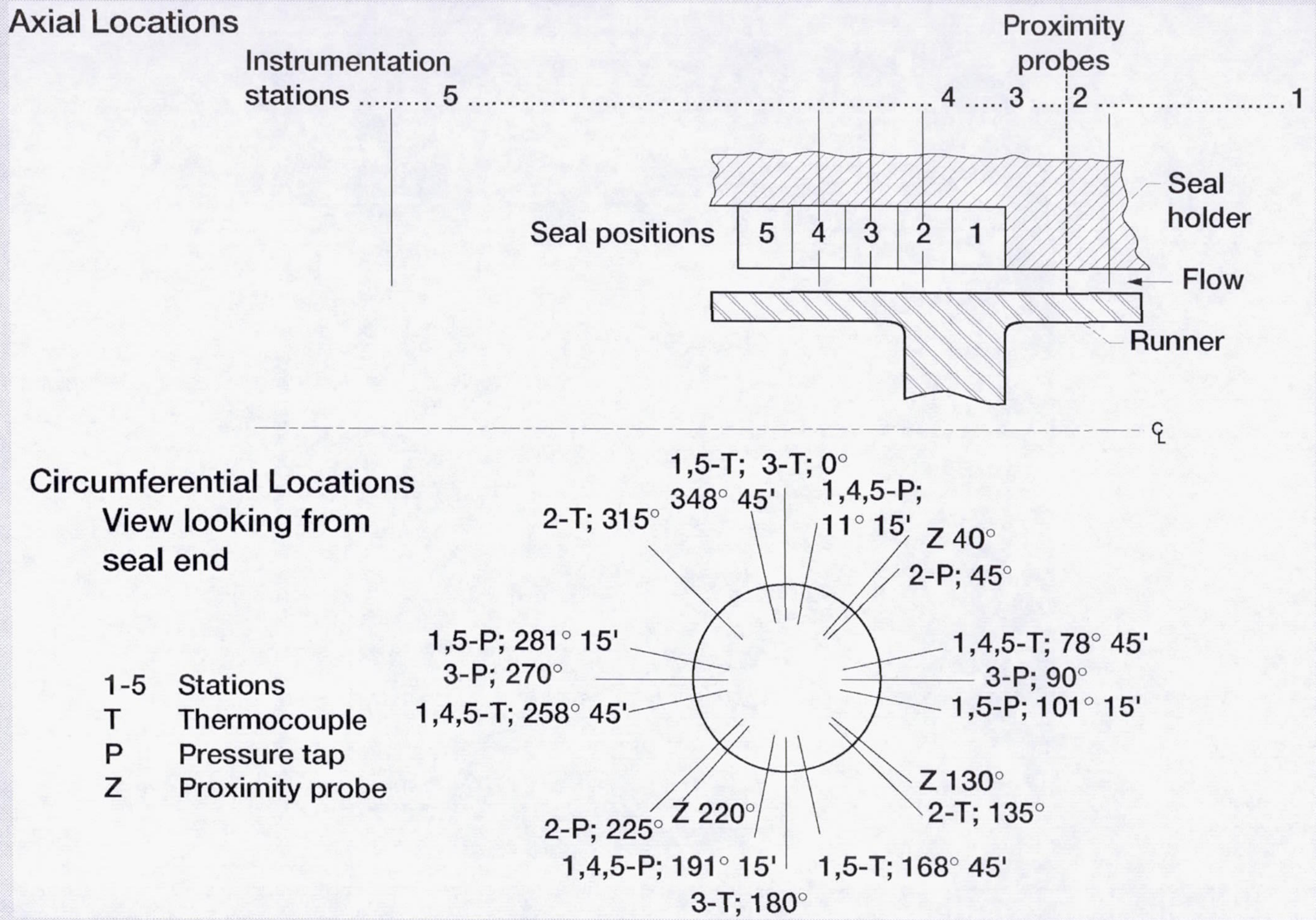
Cross Section of Cryogenic Brush Seal Tester



Some parts shown out of rotation for clarity

Location of Brush Seal Positions and Instrumentation Stations

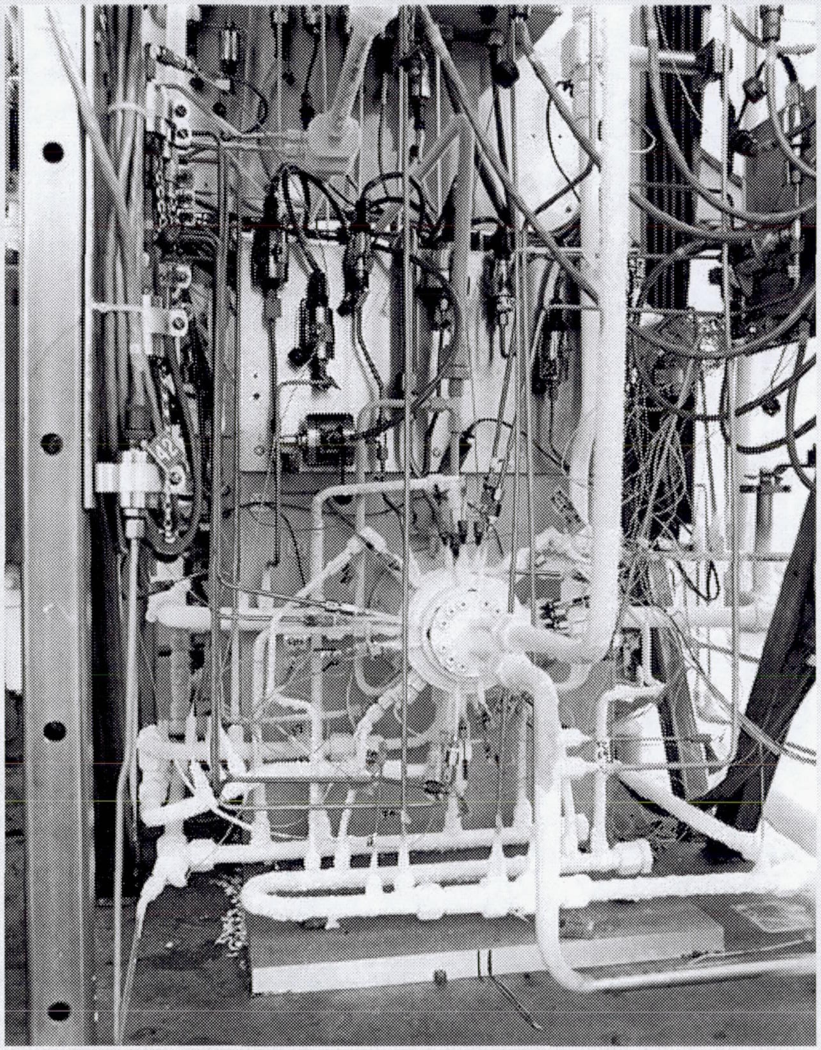
Low-Speed Runner Shown



NASA Glenn Research Center

CD-99-79873

Cryogenic Brush Seal Tester During Test



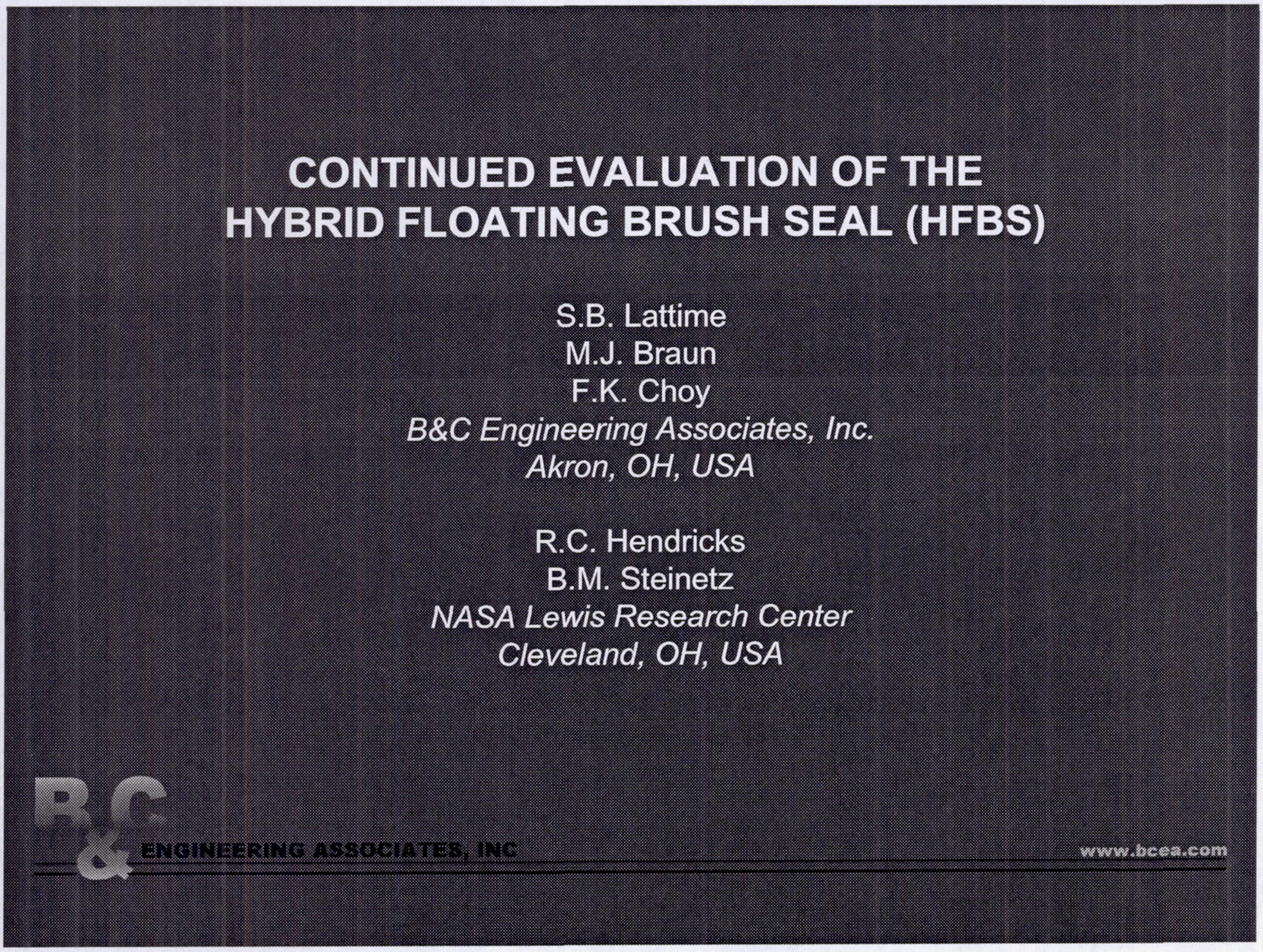
NASA Glenn Research Center

CD-99-79872

CONTINUED EVALUATION OF THE HYBRID FLOATING BRUSH SEAL (HFBS)

Scott B. Lattime, Jack Braun, and Fred K. Choy
B&C Engineering Associates, Inc.
Akron, Ohio

Robert C. Hendricks and Bruce M. Steinetz
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio



- Motivation
- HFBS Concept
- Experimental Apparatus
- Experimental Results
- Conclusions

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Motivation

- increase thrust to weight ratio
- decrease specific fuel consumption
- eliminate wear of sealing components

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HFBS Concept

- combining seal technologies
- allowing for axial & radial shaft excursions
- eliminate interface surface speeds

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HFBS Concept

- combining seal technologies
    - brush seal
    - film riding face seal
- allowing for axial & radial shaft excursions
- eliminate interface surface speeds

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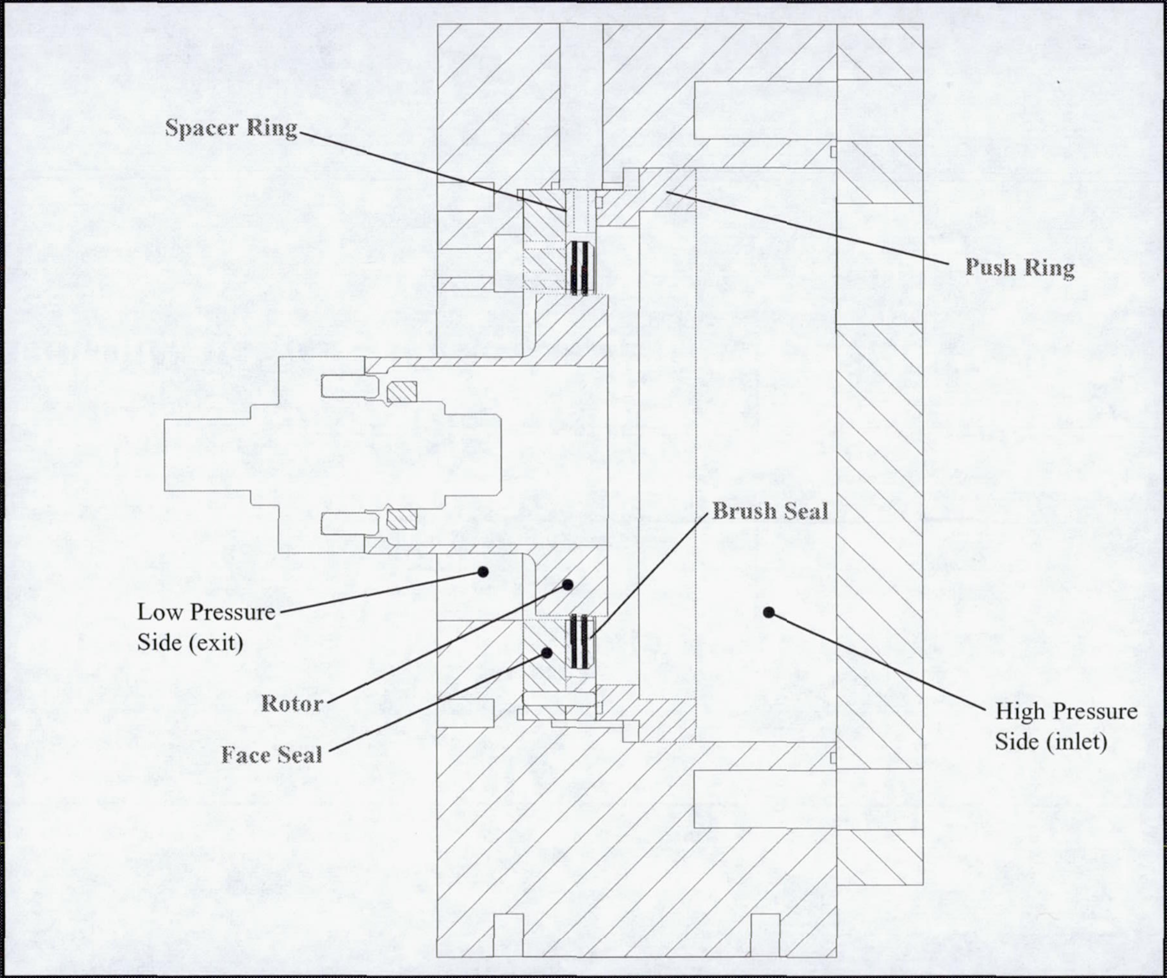
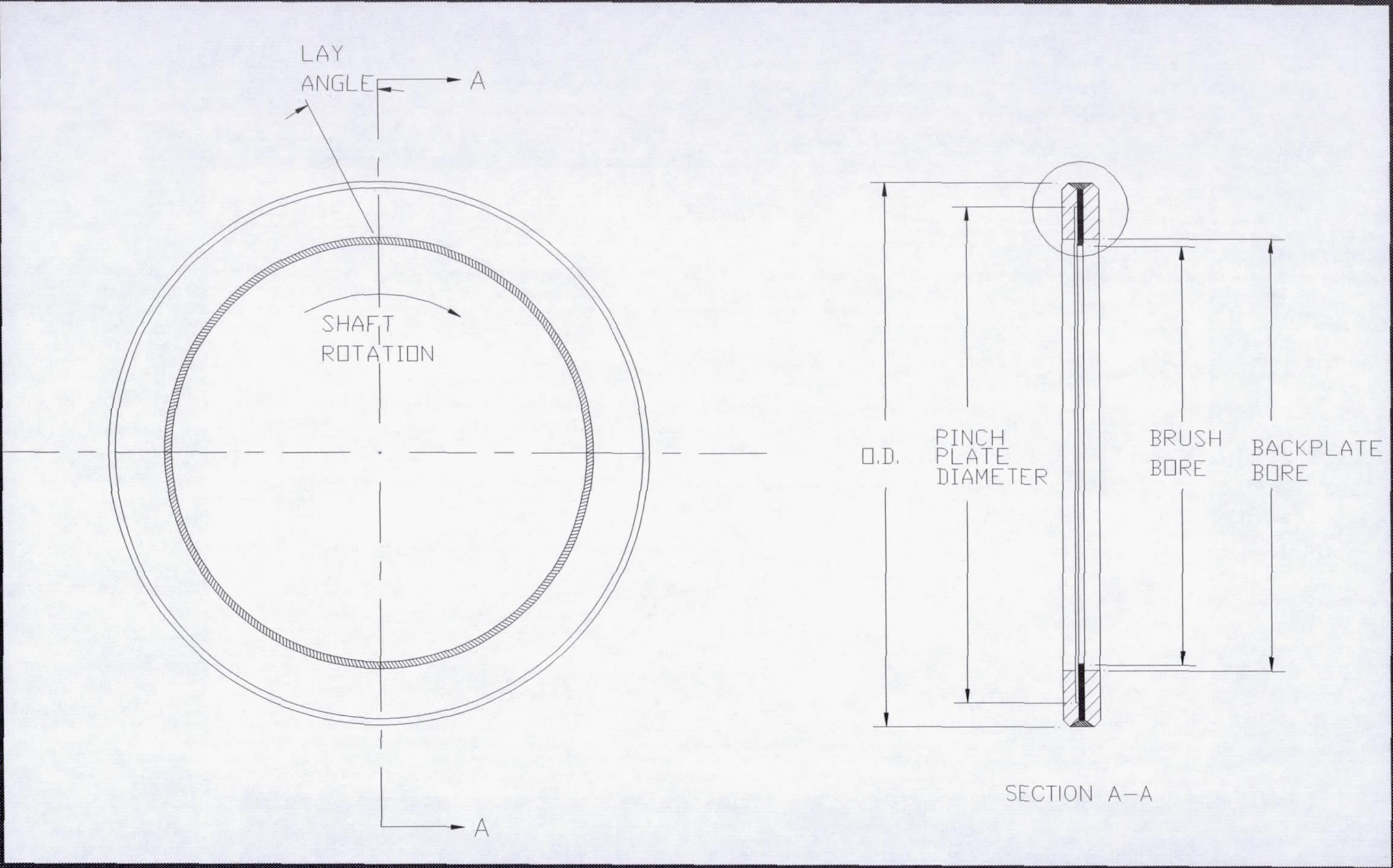

Spacer Ring
Push Ring
Brush Seal
Low Pressure
Side (exit)
Rotor
Face Seal
High Pressure
Side (inlet)



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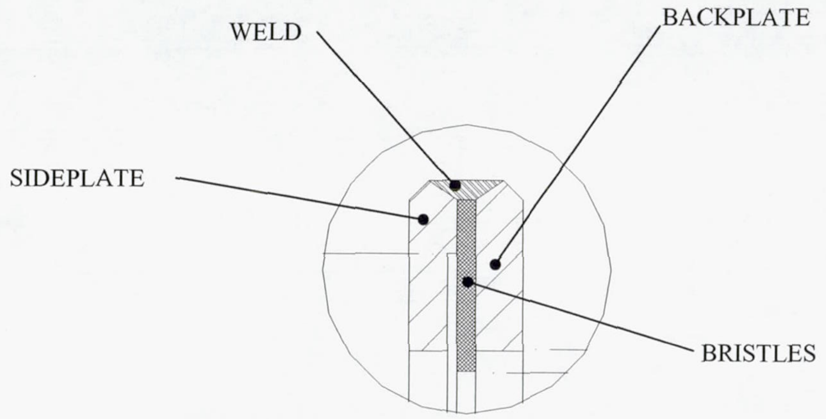

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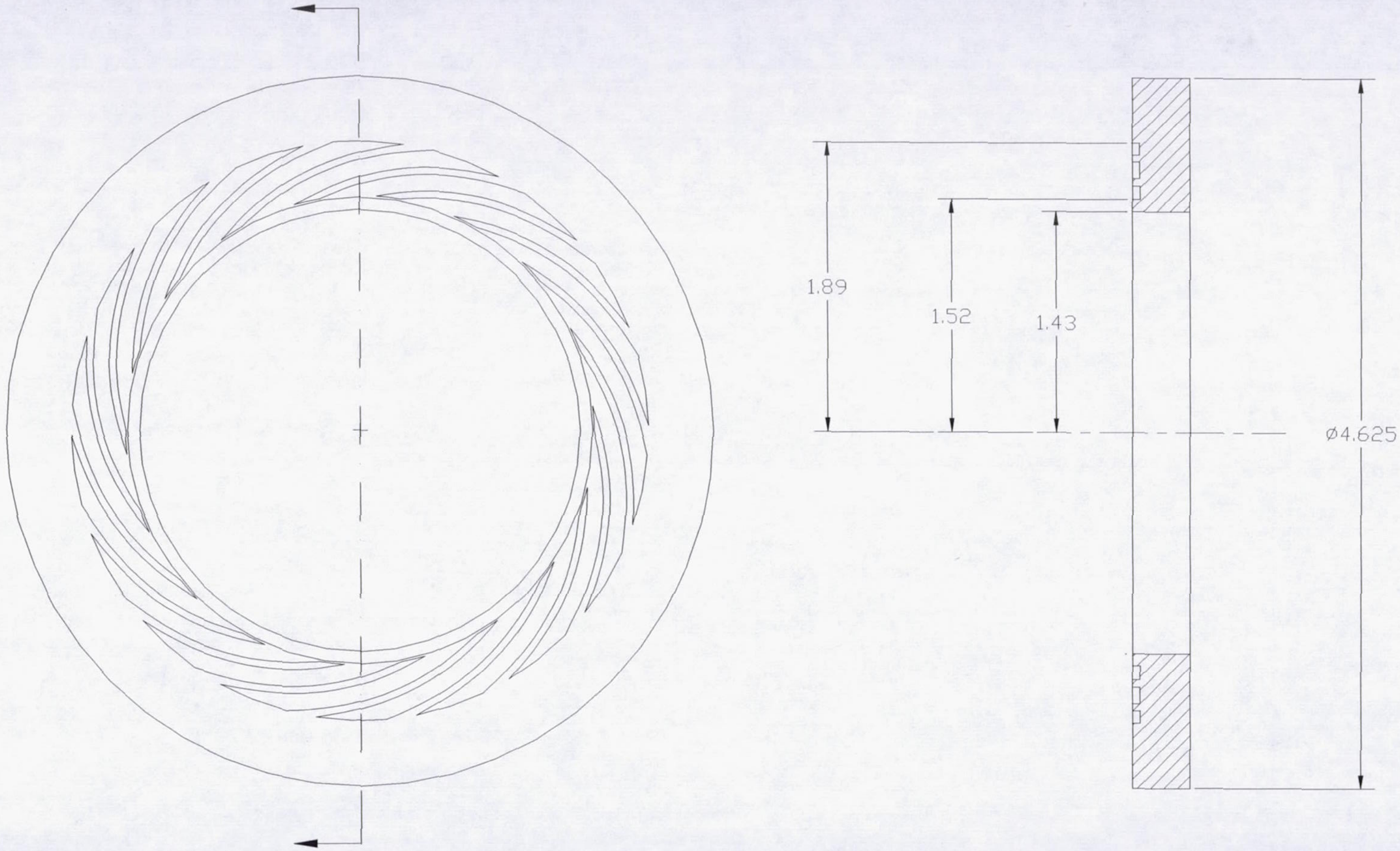

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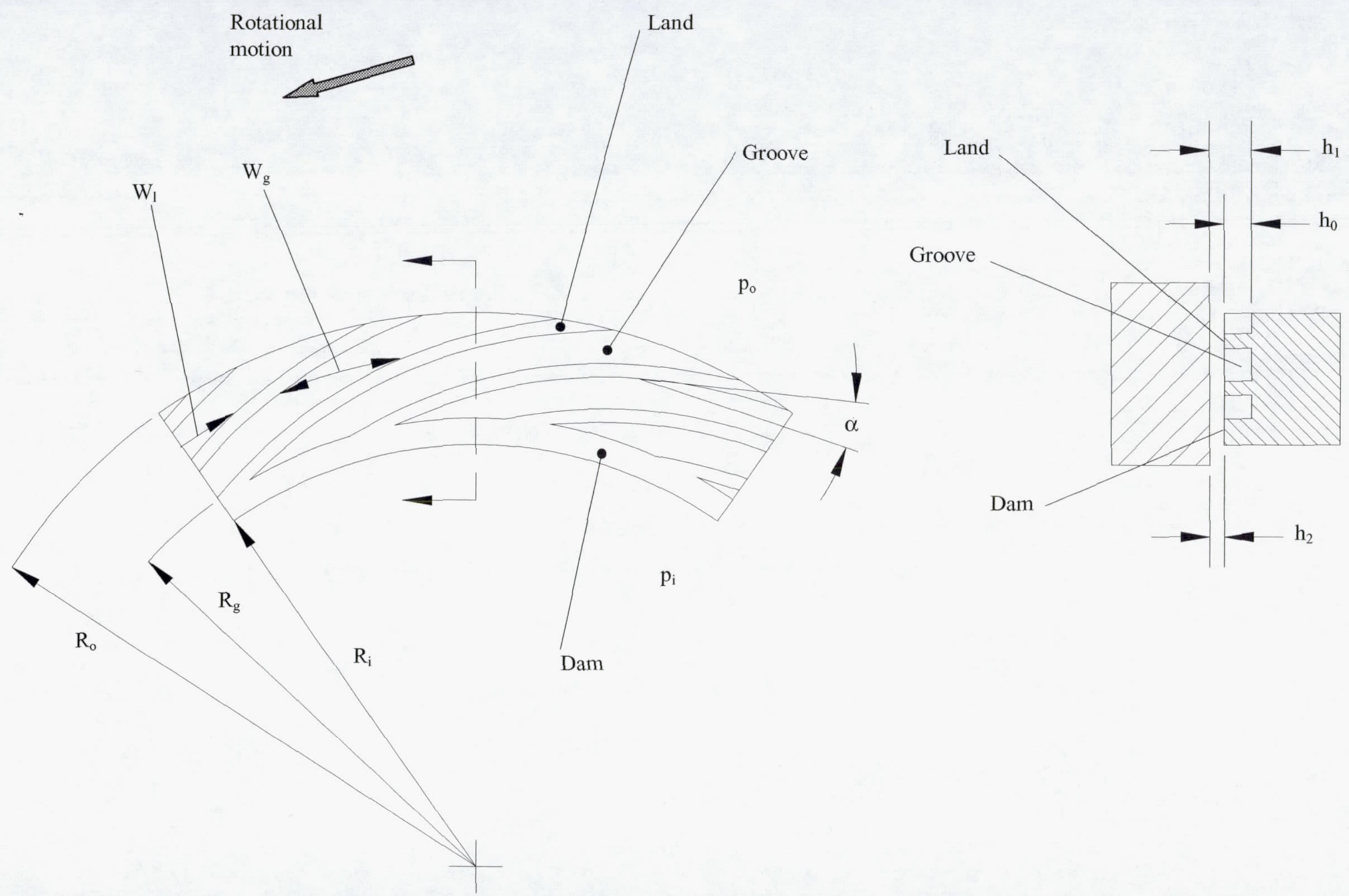
Rotational
motion
Land
Groove
Land
h1
h0
Groove
W1
Wg
po
α
Dam
h2
pi
Rg
Ro
Ri
Dam

HFBS Concept

- combining seal technologies
- allowing for axial & radial shaft excursions
    - brush seal is compliant
    - brush seal "floats" on shaft
- eliminate interface surface speeds

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HFBS Concept

- combining seal technologies
- allowing for axial & radial shaft excursions
- eliminate interface surface speeds
    - brush seal rotates with the shaft

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Experimental Apparatus

- room temperature test rig (RTTR)
- brush seals
- film riding face seal

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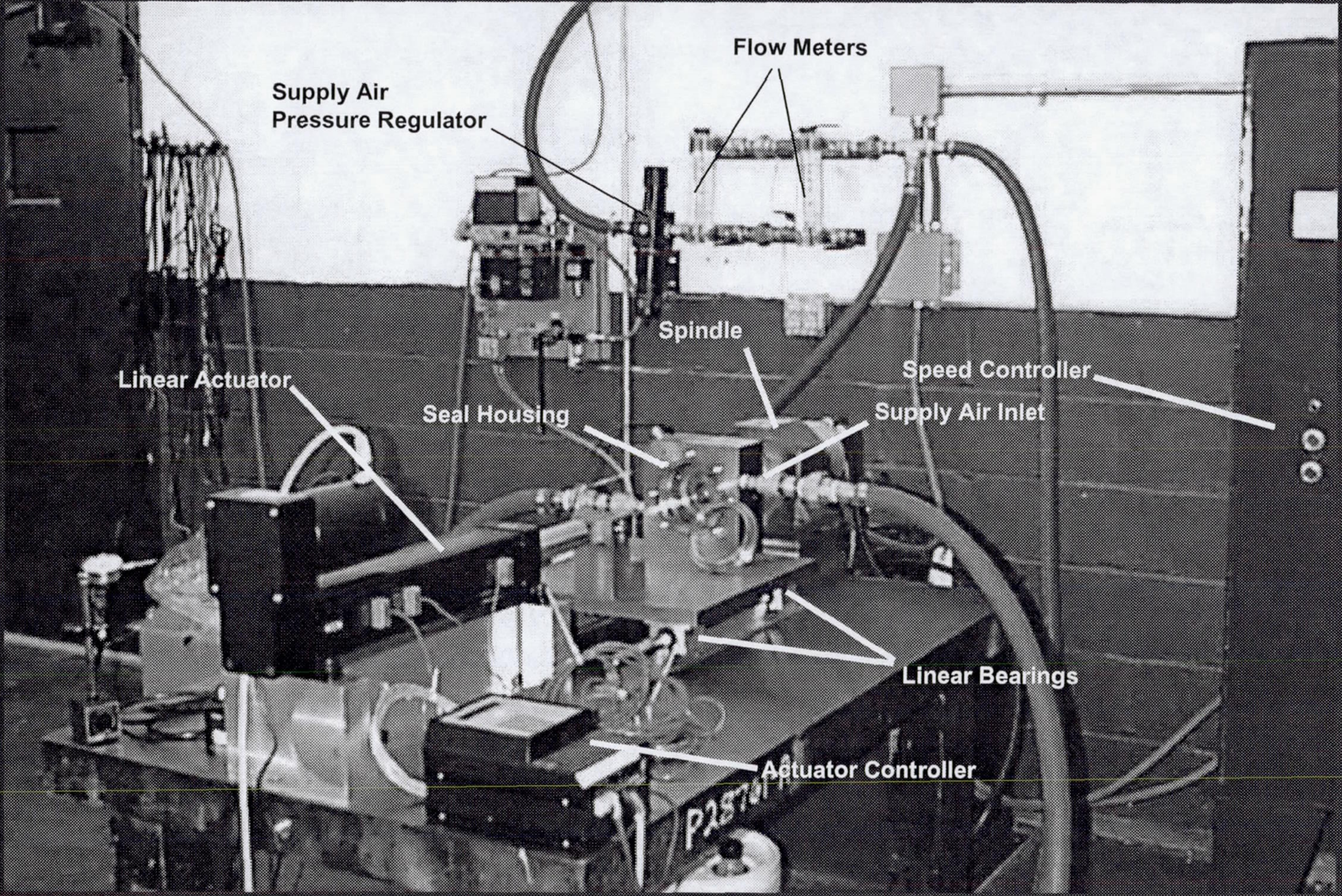
room temperature test rig (RTTR)



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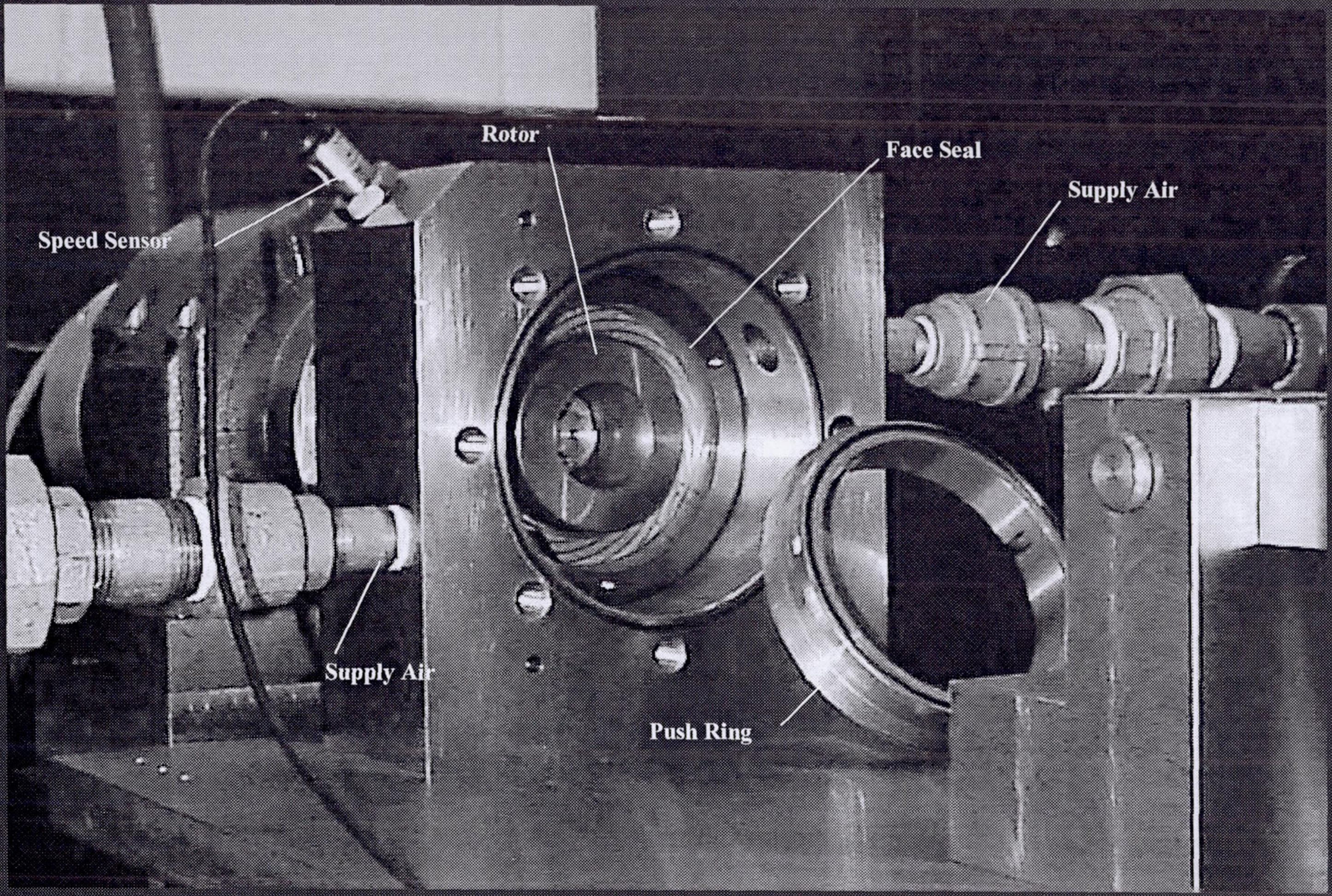

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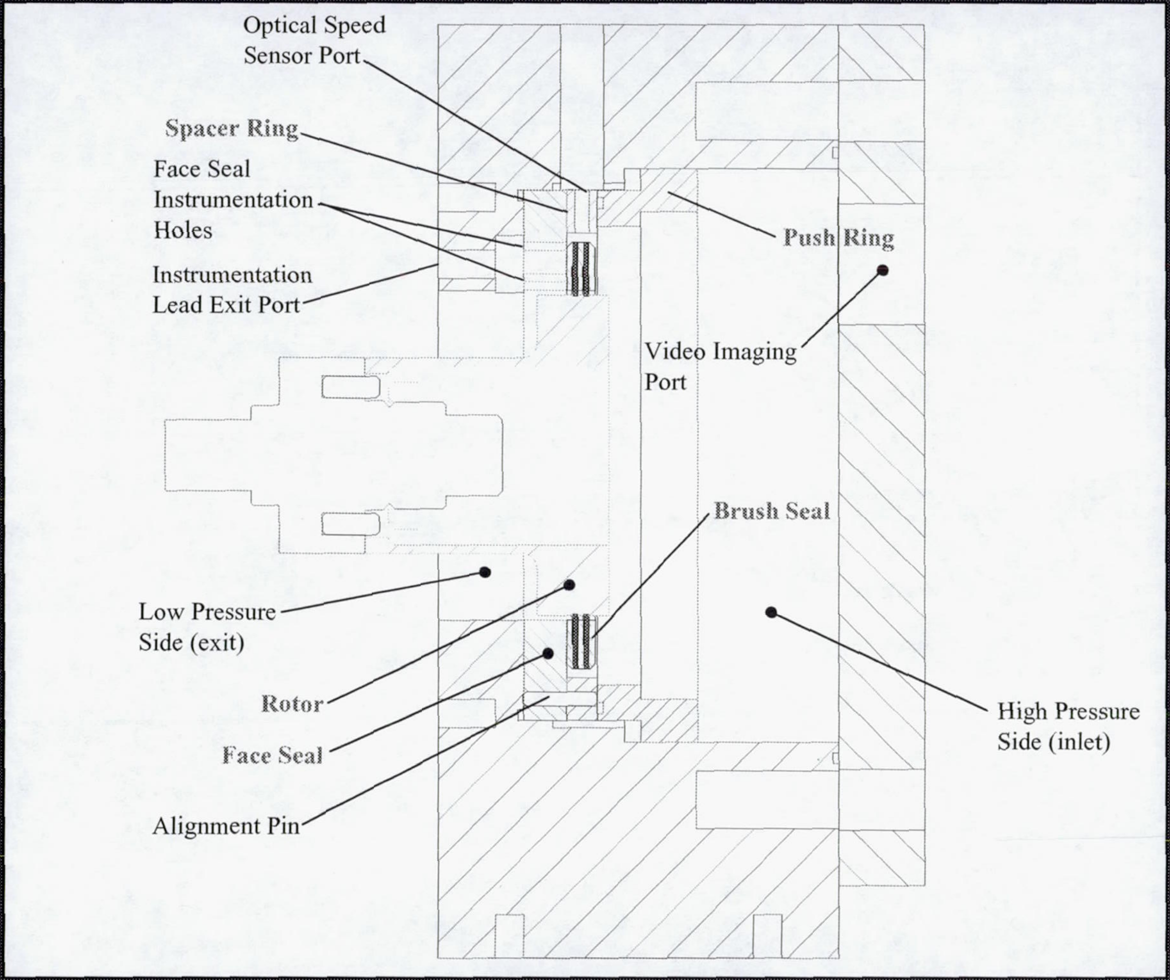

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brush seals

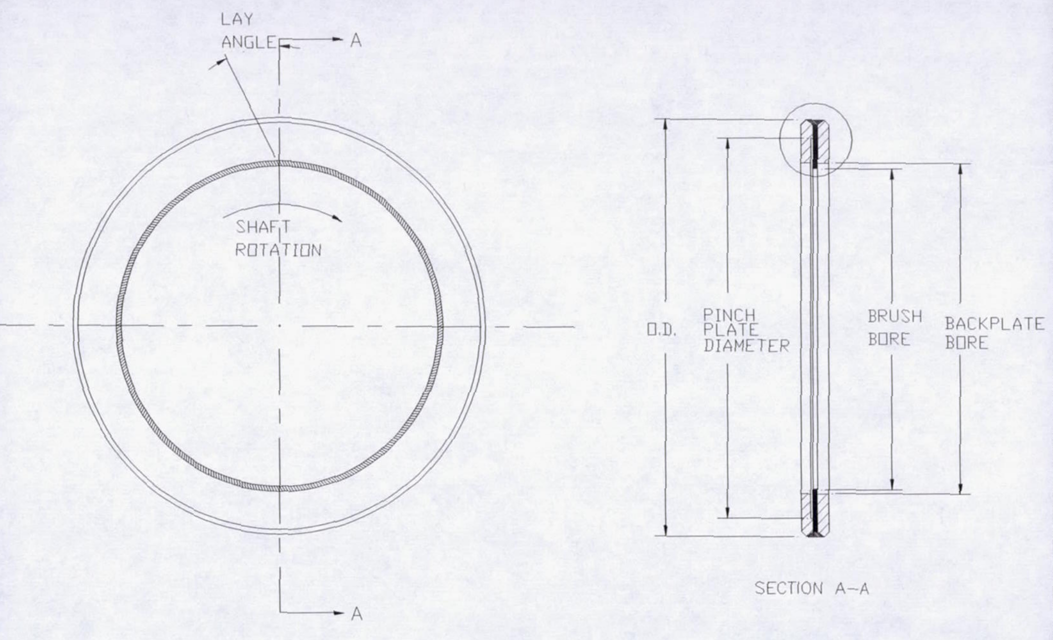

Figure 3: Single Brush Seal

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The design of a brush seal for the HFBS is significantly different from that of a stationary brush seal.

Stationary brush seals

- focus is largely on tribo-pairing the materials of the brush and the moving rotor
- reduce the wear at the interface of the two components

HFBS

- prevent the bristles from lifting off the shaft, due to centrifugal forces
- eliminate relative velocities between the two components

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Bristle Liftoff Model

The design process of the brush seal involved parametric calculations using the geometric characteristics and material properties of the bristles.

The calculations allowed the determination of the highest rotational speed at which the bristles would begin to lift off the rotor for a given bristle geometry. These properties included:

a) free length of the bristles

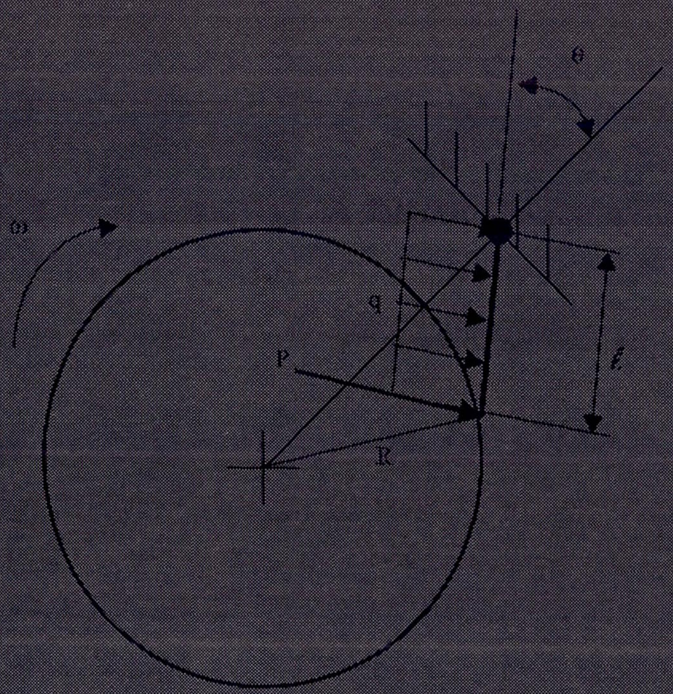
b) bristle material

c) diameter of the bristles

d) lay angle of the bristles

e) bristle pre-load

f) bending stress of the bristles



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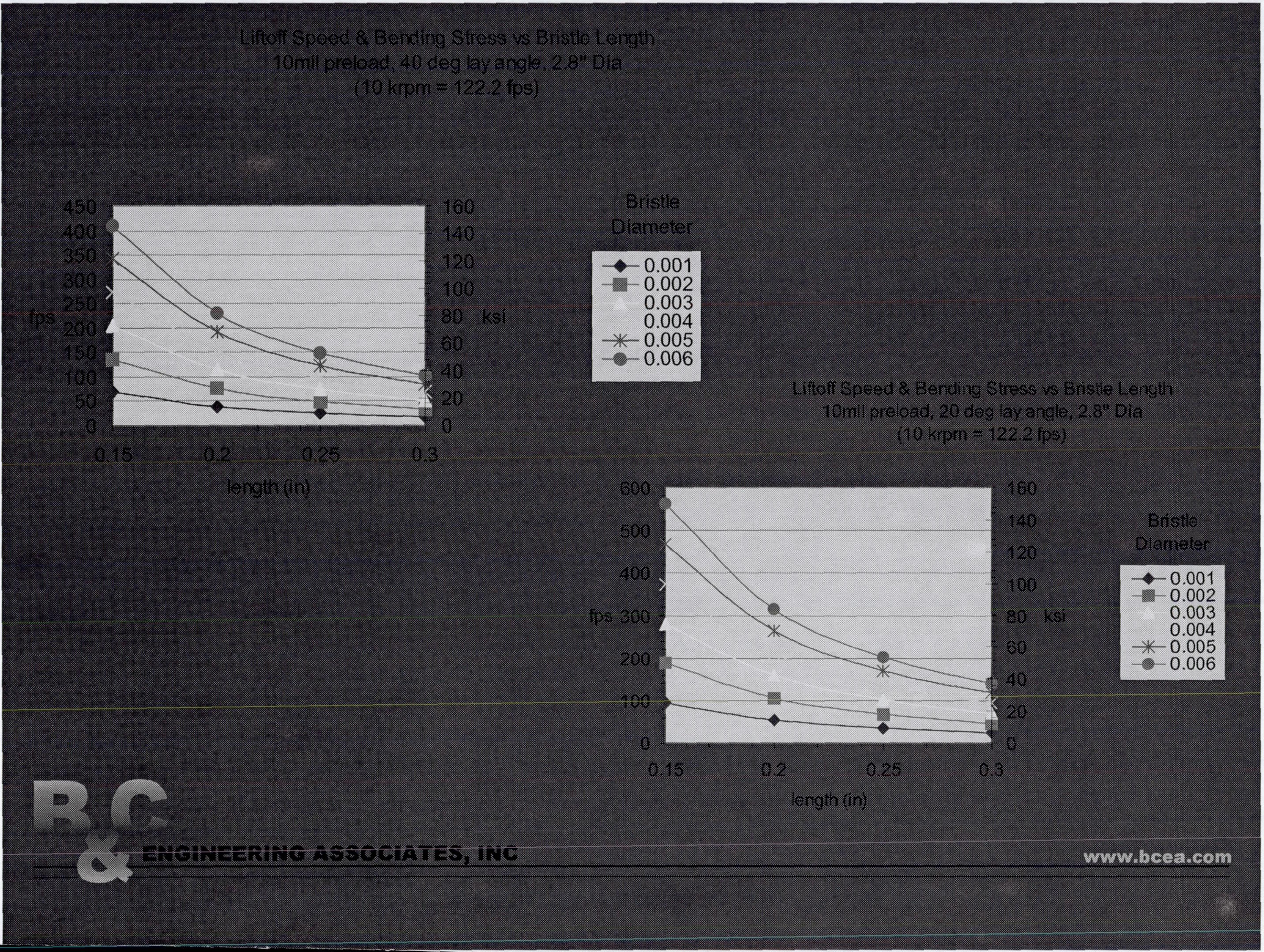
Liftoff Speed & Bending Stress vs Bristle Length
10mil preload, 40 deg lay angle, 2.8" Dia
(10 krpm = 122.2 fps)
fps
450
400
350
300
250
200
150
100
50
0
ksi
160
140
120
100
80
60
40
20
0
0.15
0.2
0.25
0.3
length (in)
Bristle Diameter
0.001
0.002
0.003
0.004
0.005
0.006
Liftoff Speed & Bending Stress vs Bristle Length
10mil preload, 20 deg lay angle, 2.8" Dia
(10 krpm = 122.2 fps)
fps
600
500
400
300
200
100
0
ksi
160
140
120
100
80
60
40
20
0
0.15
0.2
0.25
0.3
length (in)
Bristle Diameter
0.001
0.002
0.003
0.004
0.005
0.006
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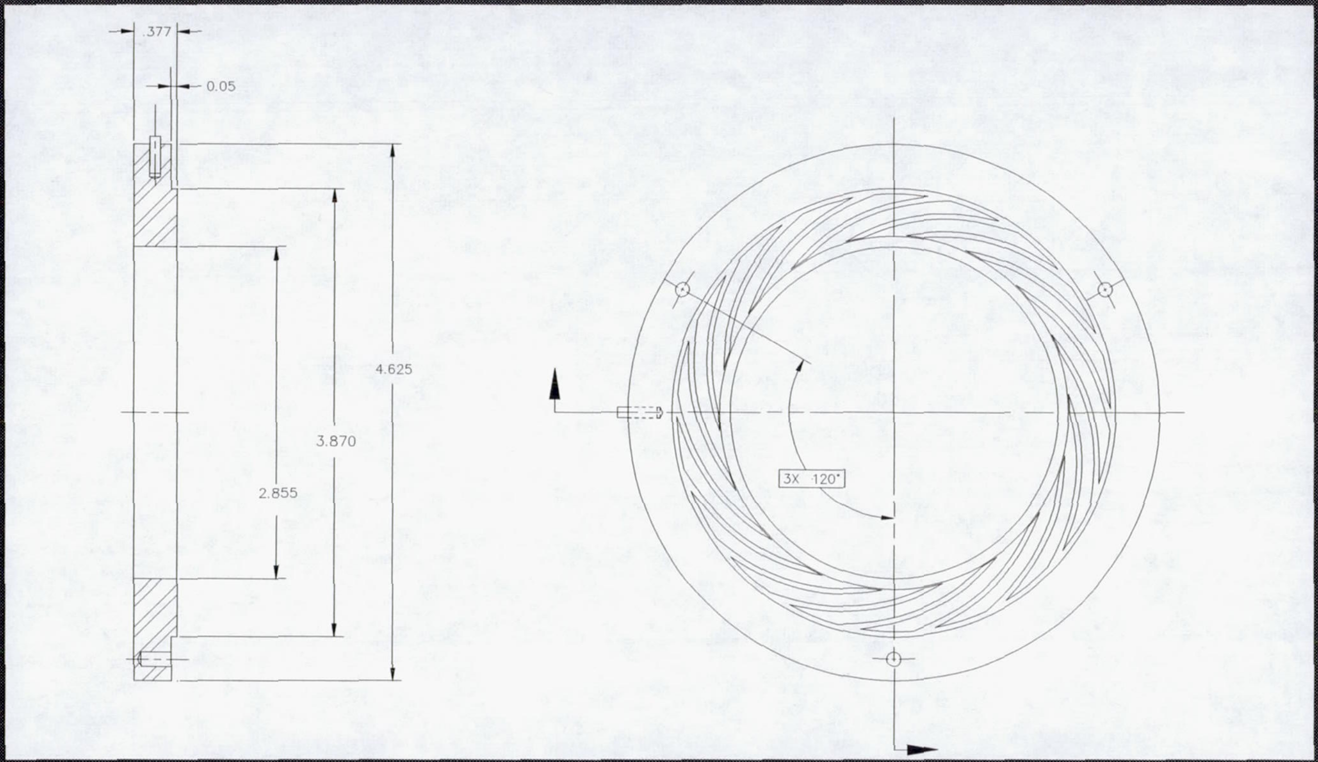
film riding face seal



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Experimental Results

- leakage performance
- axial shaft movement
- shaft radial runout

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leakage performance

Sealing performance shall be expressed in terms of a leakage flow factor ϕ.

The flow factor is defined as:

$\phi = m(Tave)/(PuD)$

where:

m	=	mass flow rate of air (pps)
Tave	=	average upstream air temperature (°R)
Pu	=	average upstream air pressure (psia)
D	=	shaft outer diameter (in)

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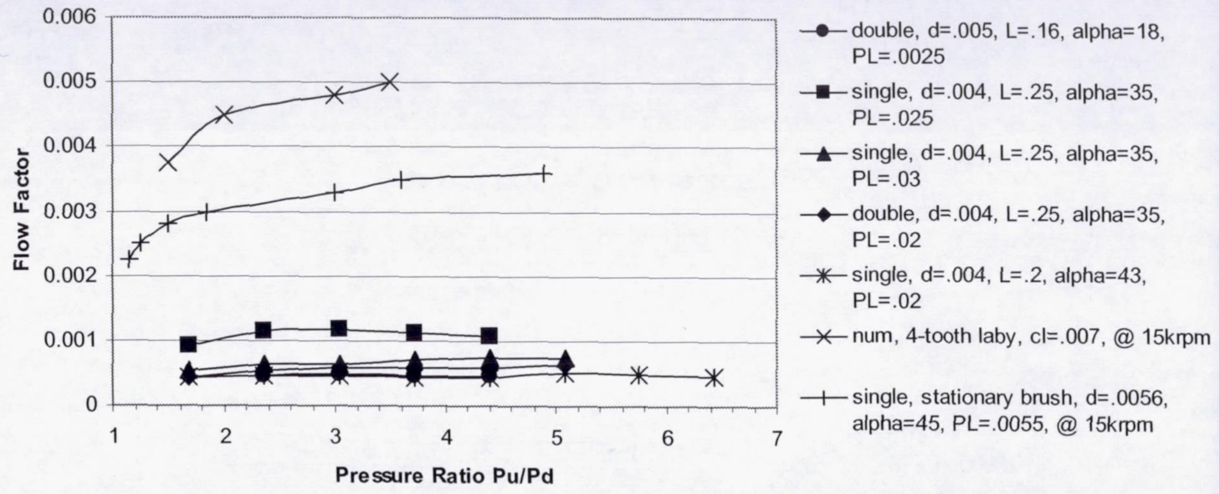

Figure 6: Leakage Performance @ 16krpm (197fps)

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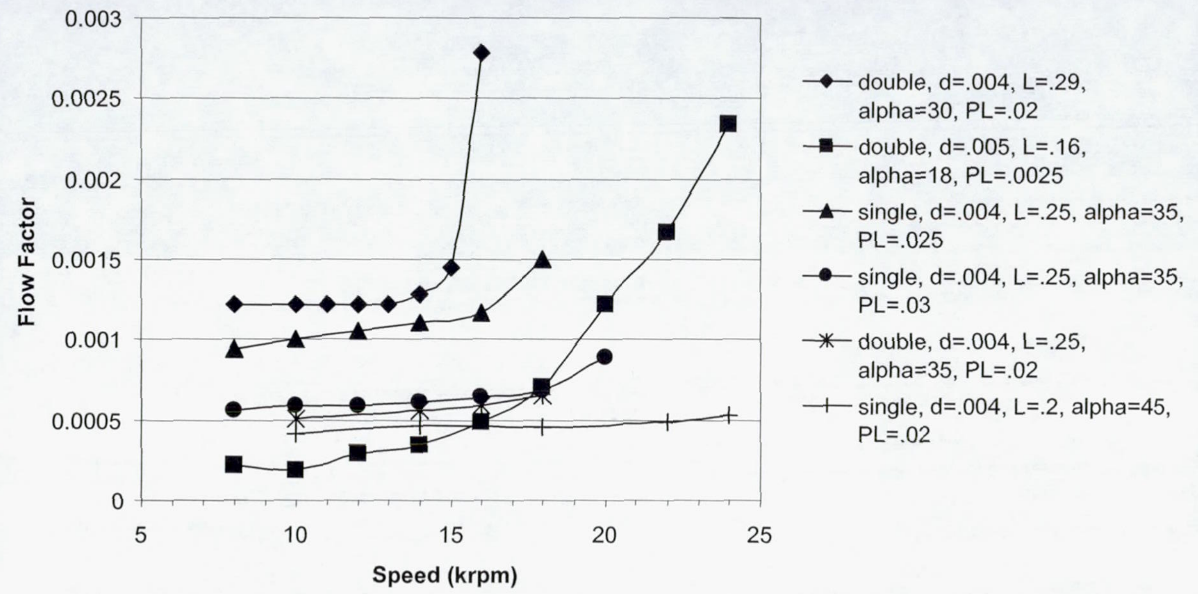

Figure 7: Leakage Performance @ P_u/P_d=3.04 (10krpm=123fps)

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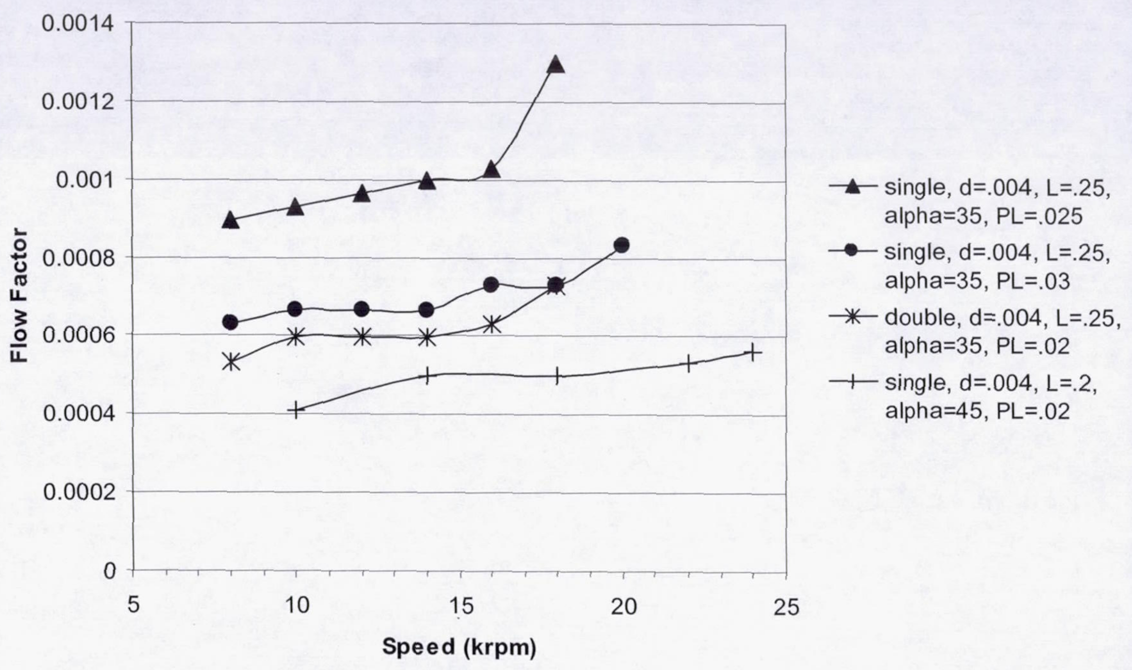

Figure 8: Leakage Performance @ P_u/P_d =5.1 (10krpm=123fps)

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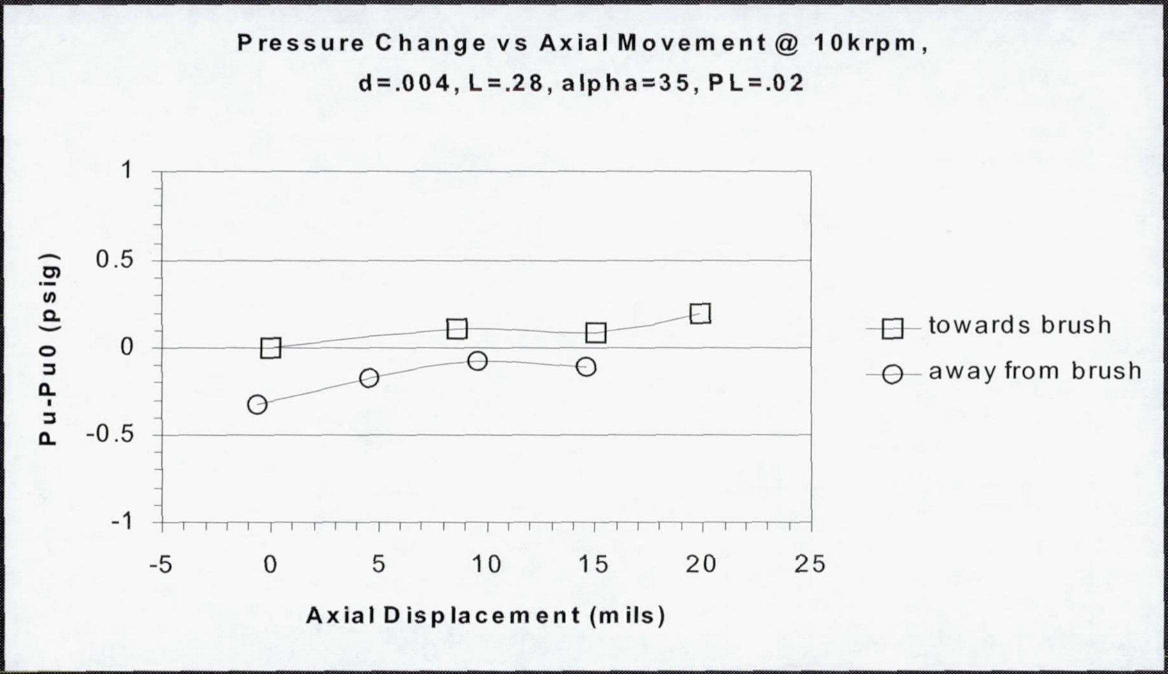
axial shaft movement



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shaft radial runout

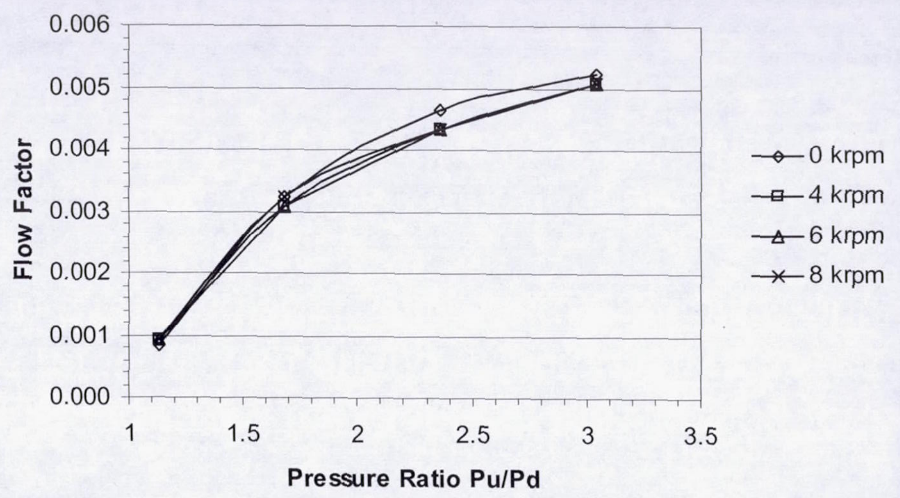

Figure 10: Seal Performance with 7mil radial runout, d=.004, L=.28, alpha=35, PL=.02 (10krpm=123fps)

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Conclusions

- verified functionality and improved sealing performance of the HFBS at relatively high operational speeds
- leakage performance acceptable for gas turbine applications
- possibility of drastically improving engine efficiency with increased sealing performance
- experimentally tested/proved the theory of the “floating” brush seal by sealing around a rotating shaft during axial motion between the shaft and seal as well as sealing a rotating shaft with a large radial runout
- capable of providing improved sealing performance with the elimination of interface wear that exists in the current "standard" brush seal technology

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EXPERIMENTAL AND NUMERICAL RESULTS OF THE COUPLED SEAL CAVITY AND MAIN FLOW FOR A LIQUID HYDROGEN ROCKET TURBOPUMP

Kerry N. Oliphant and David Japikse
Concepts ETI, Inc.
White River Junction, Vermont

EXPERIMENTAL AND NUMERICAL RESULTS OF THE COUPLED SEAL CAVITY AND MAIN FLOW FOR A LIQUID HYDROGEN ROCKET TURBOPUMP

Kerry N. Oliphant and David Japikse
Concepts ETI, Inc.

STUDY OF THE SSME LH_2 HIGH PRESSURE TURBOPUMP

- Phase 1 and 2 SBIR grant.
- Apply advanced pump and compressor technology to alternate design.
  - good throttleability
  - high efficiency
  - reduced part count
- Investigate front and rear leakage cavities.
  - Coupled cavity-impeller flow character.
  - Effects on thrust balance.

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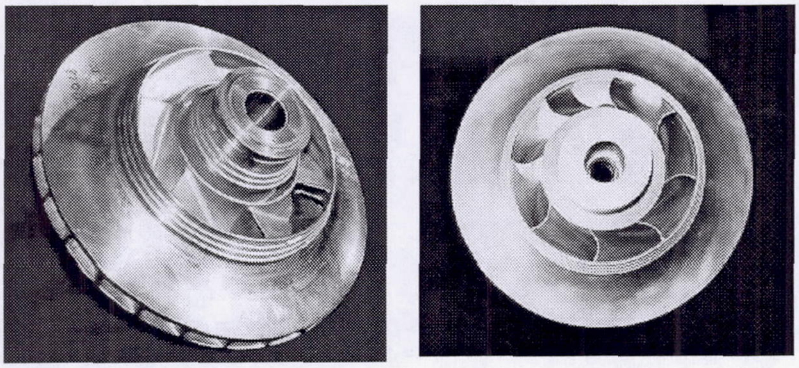
COMPARISON OF LH2 FIRST-STAGE SSME ROCKET TURBO PUMP IMPELLER WITH ADVANCED TECHNOLOGY IMPELLER



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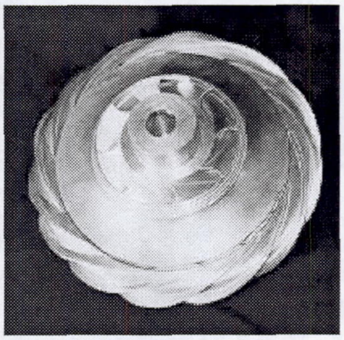
Conventional LH2 st stage SSME rocket turbopump compared to advanced technology impeller.

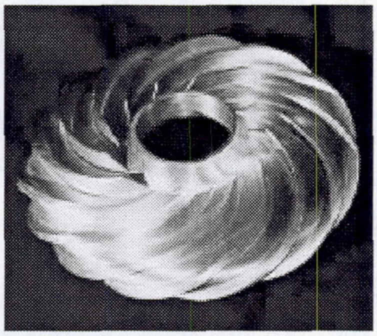
increased inlet blade count from 6 to 8

reduced splitter count from 2 rows to 1 row
exit blade count went from 24 to 16

simplified design

MODIFIED CONTINOUS CROSSOVER DESIGN CONFIGURATION





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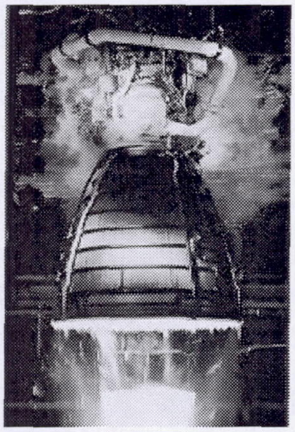
Simpler design

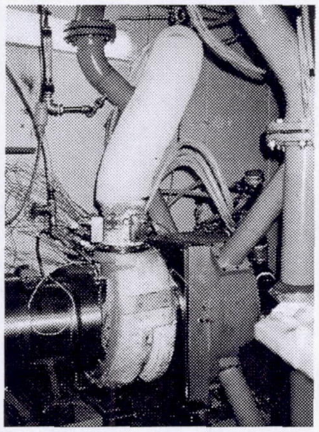
Based on a diffusing vane concept

Substantial reduction in overall diameter with good performance.

Translates to reduced size and weight.

TURBOPUMP TESTED BEHIND THE BILL-OF-MATERIALS SSME LH2 TURBOPUMP INLET ELEMENT





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Original SSME LH2 pump and alternative design tested in water rig.

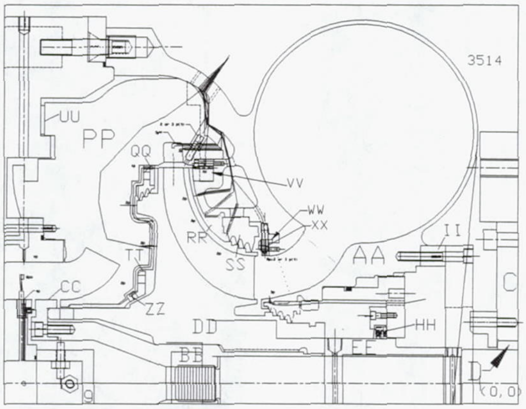
Magnetic bearing rig used to measure radial and axial loads.

Important for thrust measurements for the investigation of the various seal cavity configurations.

Comparison to the CFD predicted axial thrust.

Actual SSME inlet elements used. The inlet pipe and the inlet volute with IGV's

TEST RIG LAYOUT AND MEASUREMENT LOCATIONS



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Point out the various components and seals.

In addition to the axial thrust measurements other instrumentation was included to assess the performance of the stage and investigate the influence of the seal cavities on the performance.

Static pressure taps:

Inlet (hub, tip)

Impeller exit (hub, tip)

Return exit (hub)

3 locations through the front cavity seal

more taps for configuration with bleed at the back face that is not reported here.

Keil probes:

Diffuser throat

Crossover exit.

Previous testing traversed behind the IGV's of the inlet element to get the flow velocity and angle distribution into the impeller. This information was used for the boundary conditions on the CFD calculations.

CFD MODEL OF THE ALTERNATIVE DESIGN TURBOPUMP

- Model the impeller coupled with the front and rear seal cavities.
- Investigate the flow field inside the seal cavities and compare to test data.
- Investigate the interaction between the seal cavities and the main flow
- Predict axial thrust to compare to test data.

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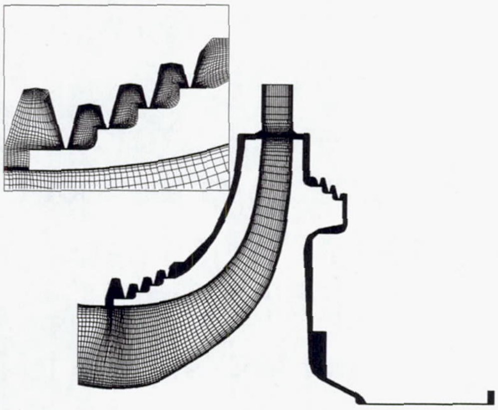
MERIDIONAL VIEW OF MESH WITH FRONT AND BACKFACE CAVITIES



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Structured Multi-block mesh in impeller and seal cavities created with GridPro.

Care was taken to capture important details of the seal cavities.

Mesh clustered in the main flow path to resolve boundary layer.

Boundary Conditions:

1.) Inlet distribution of velocity and flow angle taken from traverses behind the inlet element.

2.) Mass flow was imposed at back face seal cavity to match the measured pressure drop.

FINE/Turbo^{TM} CFD PACKAGE WAS USED FOR THE SIMULATION

- Multi-block structured code
- Central difference discretization
- Time-marching with preconditioning for incompressible flow
- Baldwin-Lomax turbulence model
  - First node spacing y+ ~ 2
  - Reasonable performance in boundary layer dominated flows (main flow path)

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WATER WAS USED FOR THE TEST AND CFD SIMULATION

- Appropriate flow rate and speed was selected for correct similarity scaling between LH_2 and Water.
- Water rig mass flow = 54.3 lbm/s
- Water rig speed = 889 RPM

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TEST DATA PARAMETERS COMPARED TO CFD RESULTS

Parameter	Units	Data	CFD
Mass Flow	lbm/s	54.3	54.4
Wheel Speed	RPM	889	889
Inlet Total Pressure (P00)	psia	22.42	22.43
Impeller Exit Static Pressure (P2)	psia	33.28	32.89
Impeller Exit Total Pressure (P02)	psia	-	42.25
Diffuser Throat Total Pressure (P04)	psia	42.04	-
Shaft Power	hp	5.22	4.82
Total-to-Total Impeller Efficiency (η_{tt})		0.89	0.94
Total-to-Static Impeller Efficiency (η_{ts})		0.47	0.49
Axial Thrust	lbf	768	840
Front Seal Cavity Flow	lbm/s	-	0.50
Rear Seal Cavity Flow	lbm/s	-	0.33

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3.5% low in pressure rise prediction

2 points high in static to static efficiency

5 points high in total-to-total efficiency estimate - but we don't have a good number for the the impeller exit total pressure

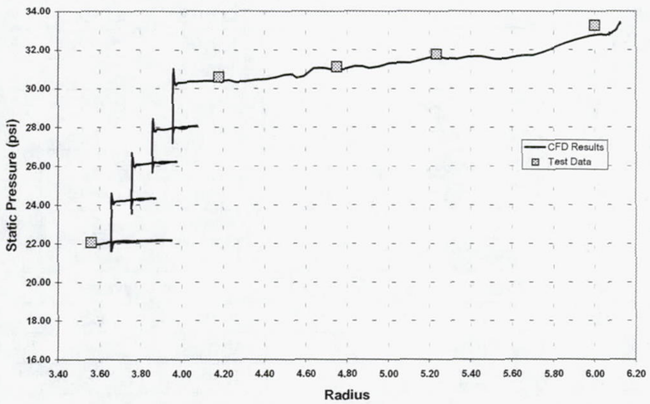
7.5% low in shaft power

didn't get the skin friction right on the seal cavity walls

Axial thrust is high by about 9%

Predicted seal cavity mass flows are on the order (percentage wise) of what was assumed in the SSME engine.

COMPARISON OF CFD PREDICITONS TO TEST DATA OF STATIC PRESSURE ALONG FRONT SEAL CAVITY OUTER WALL



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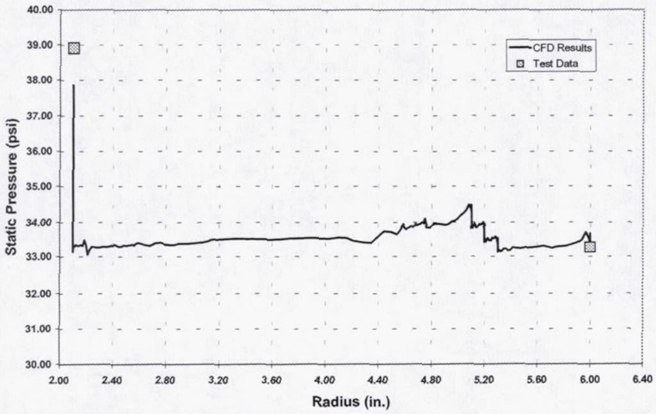
Generally good agreement between test data and CFD results.

Clearly see the drop in pressure across the seal teeth.

Predictions are a little bit low in static pressure towards the tip. If we integrate the difference in static pressure in the tip region we come up with a value of about 19 pounds force due to the difference. This is about 2.5% of the higher predicted thrust value

The other 6 or 7% difference has to be tied up in the rear seal cavity predicted pressure distribution.

COMPARISON OF CFD PREDICTIONS TO TEST DATA OF STATIC PRESSURE ALONG REAR SEAL CAVITY WALL



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Mass flow adjusted to try and match the pressure drop.

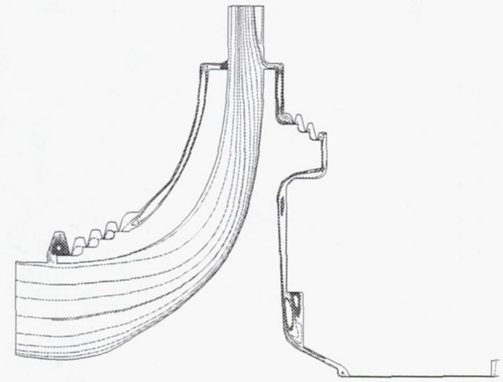
Unfortunate that we didn't have internal static taps to see which parts of the backface, if any, that we are getting right

Significant influence of the damper seal on the pressure drop and mass flow through the cavity. Small variations in the test build could have large impact.

See the gradual pumping of the fluid up to the labyrinth seals.

Pressure distribution is highly dependent on the mass flow. Implies that we don't have the right mass flow imposed through the back face seal. Should run this coupled to the crossover return.

STREAMLINES IN MAIN FLOW PATH AND THE FRONT AND REAR SEAL CAVITIES



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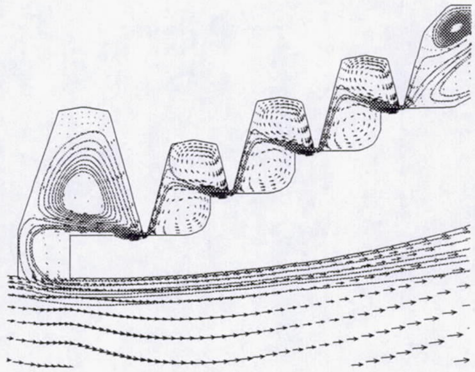
VELOCITY VECTORS AND STREAMLINES SHOW THE DETAILS OF THE FLOW IN THE FRONT CAVITY LABYRINTH SEALS



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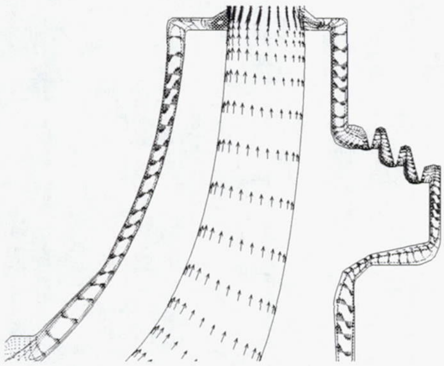
VELOCITY VECTORS AND STREAMLINES - DETAILS OF FLOW IN THE FRONT SEAL CAVITY AND REAR CAVITY LABY SEALS



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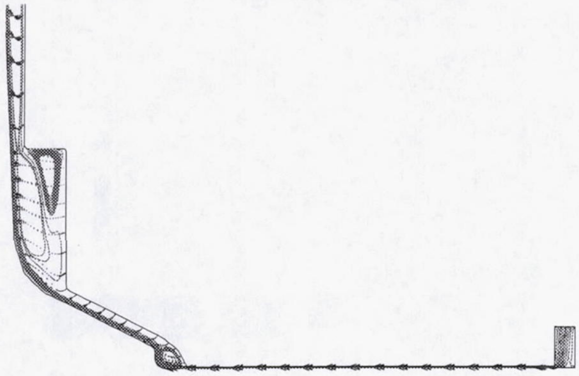
VELOCITY VECTORS AND STREALINES SHOW DETAILS OF FLOW IN THE BACK CAVITY NEAR DAMPER SEAL



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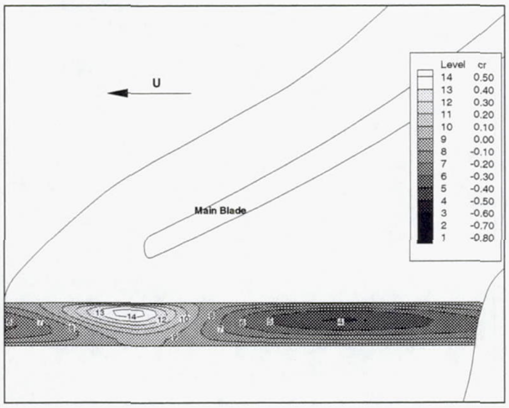
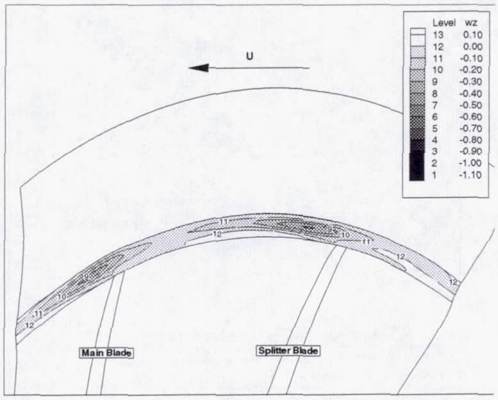
RADIAL COMPONENT OF VELOCITY CONTOURS AT LOCATION OF SEAL CAVITY INJECTION INTO IMPELLER EYE



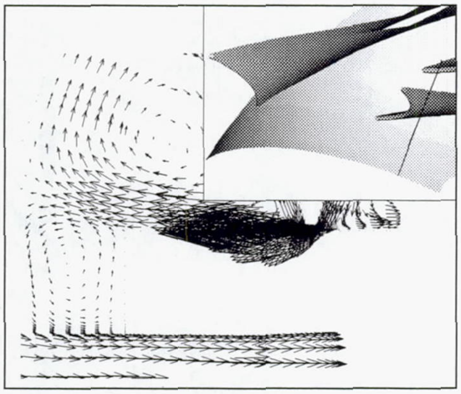
CONCEPTS ETI, INC.

AXIAL COMPONENT OF VELOICTY CONTOURS AT LOCATION OF SEAL CAVITY INJECTION FROM IMPELLER EXIT



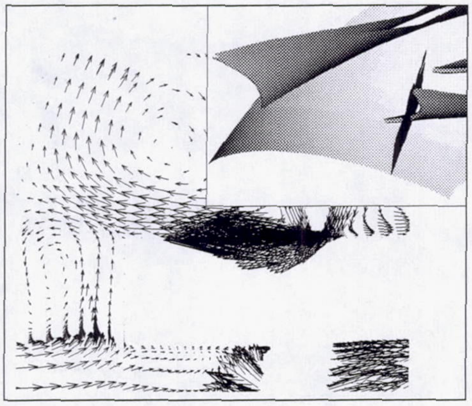
CONCEPTS ETI, INC.

VELOCITY VECTORS AT IMPELLER EYE INJECTION LOCATION ($\theta = 0.0°$)



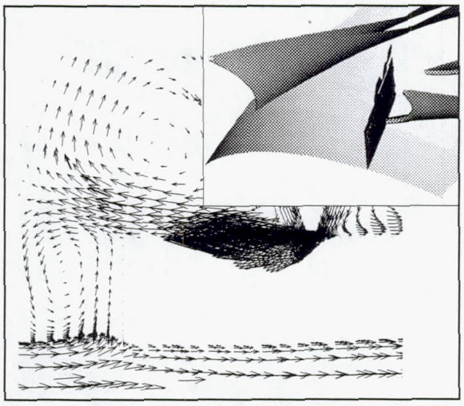
CONCEPTS ETI, INC.

VELOCITY VECTORS AT IMPELLER EYE INJECTION LOCATION ($\theta = 5.0°$)



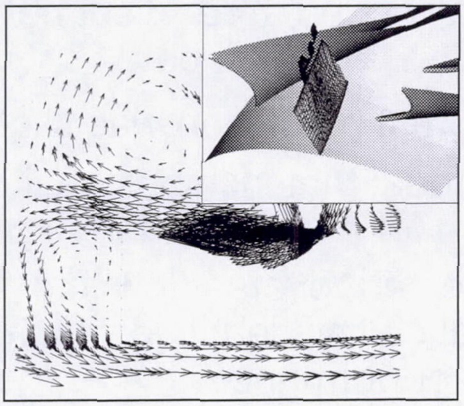
CONCEPTS ETI, INC.

VELOCITY VECTORS AT IMPELLER EYE INJECTION LOCATION ($\theta = 10.0°$)



CONCEPTS ETI, INC

VELOCITY VECTORS AT IMPELLER EYE INJECTION LOCATION ($\theta = 25.0°$)



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CONCLUSIONS

- Generally good agreement between CFD predictions and test data.
- Axial thrust prediction was slightly high.
- CFD model that includes seal cavities can be used for good axial thrust predictions.
- Unexpected reverse flow into and out of the seal cavity identified which could impact performance.

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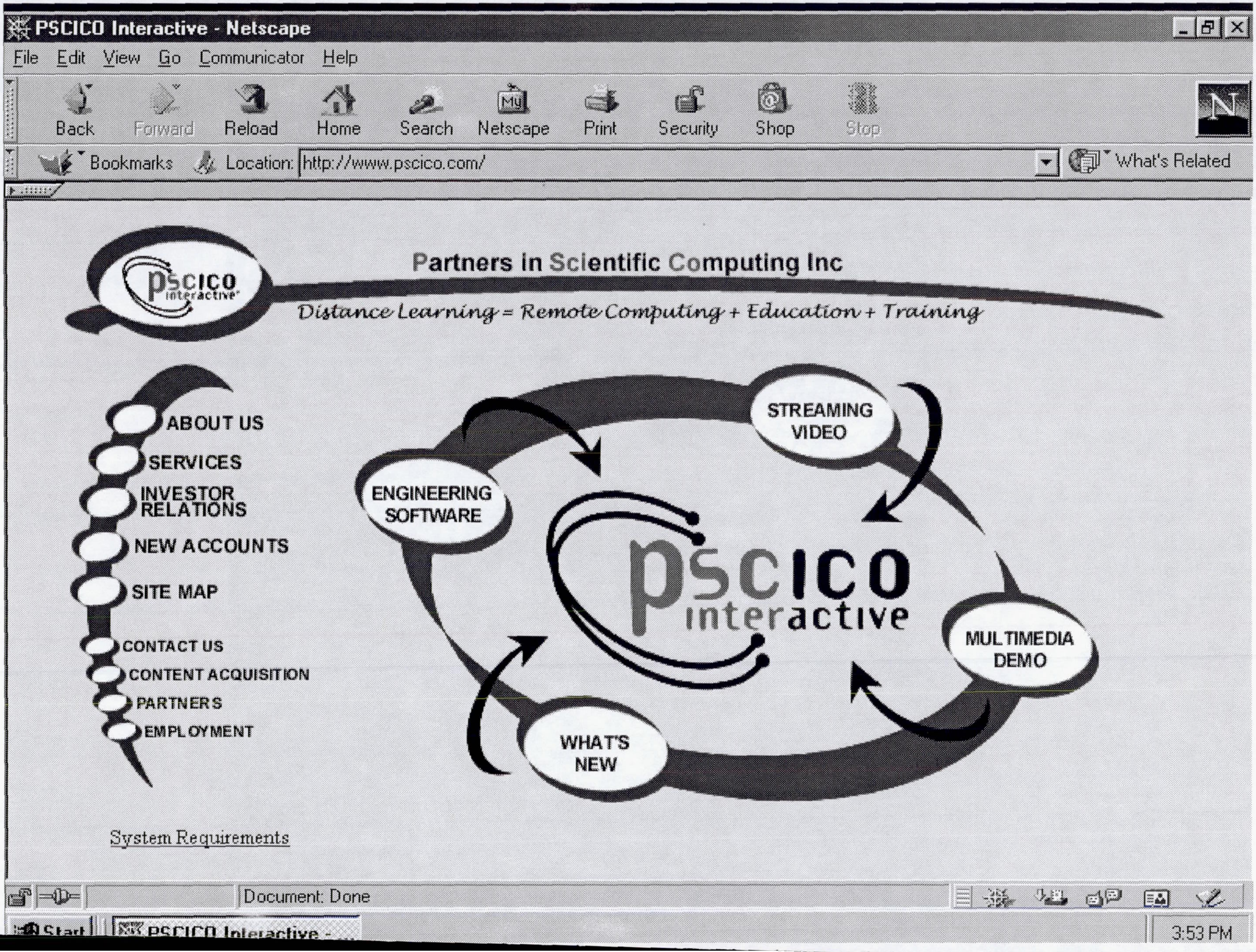
ENGINEERING AND SCIENTIFIC COMPUTATION OVER THE INTERNET

Jack Braun
PSICO: Partners in Scientific Computing
Akron, Ohio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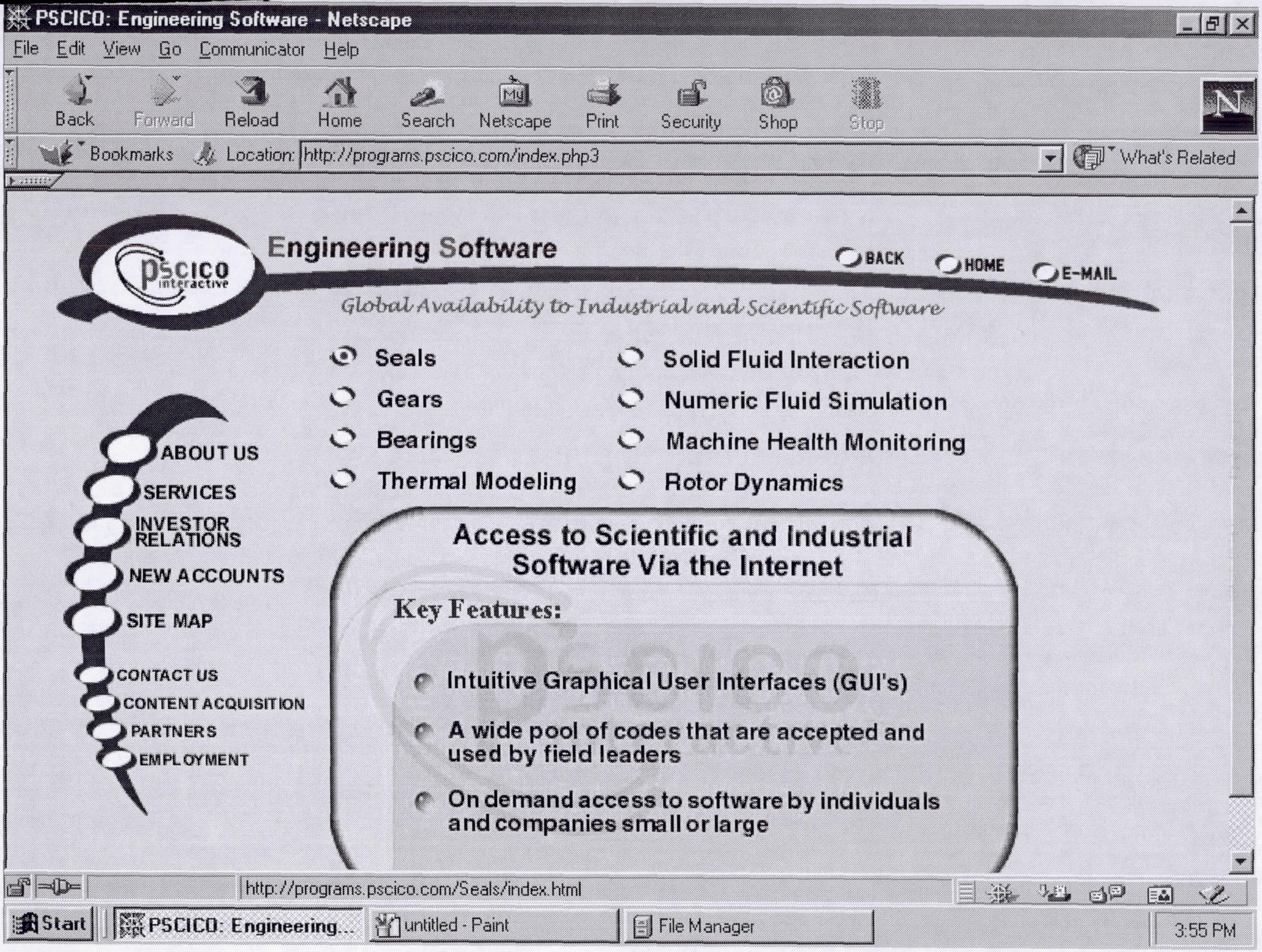
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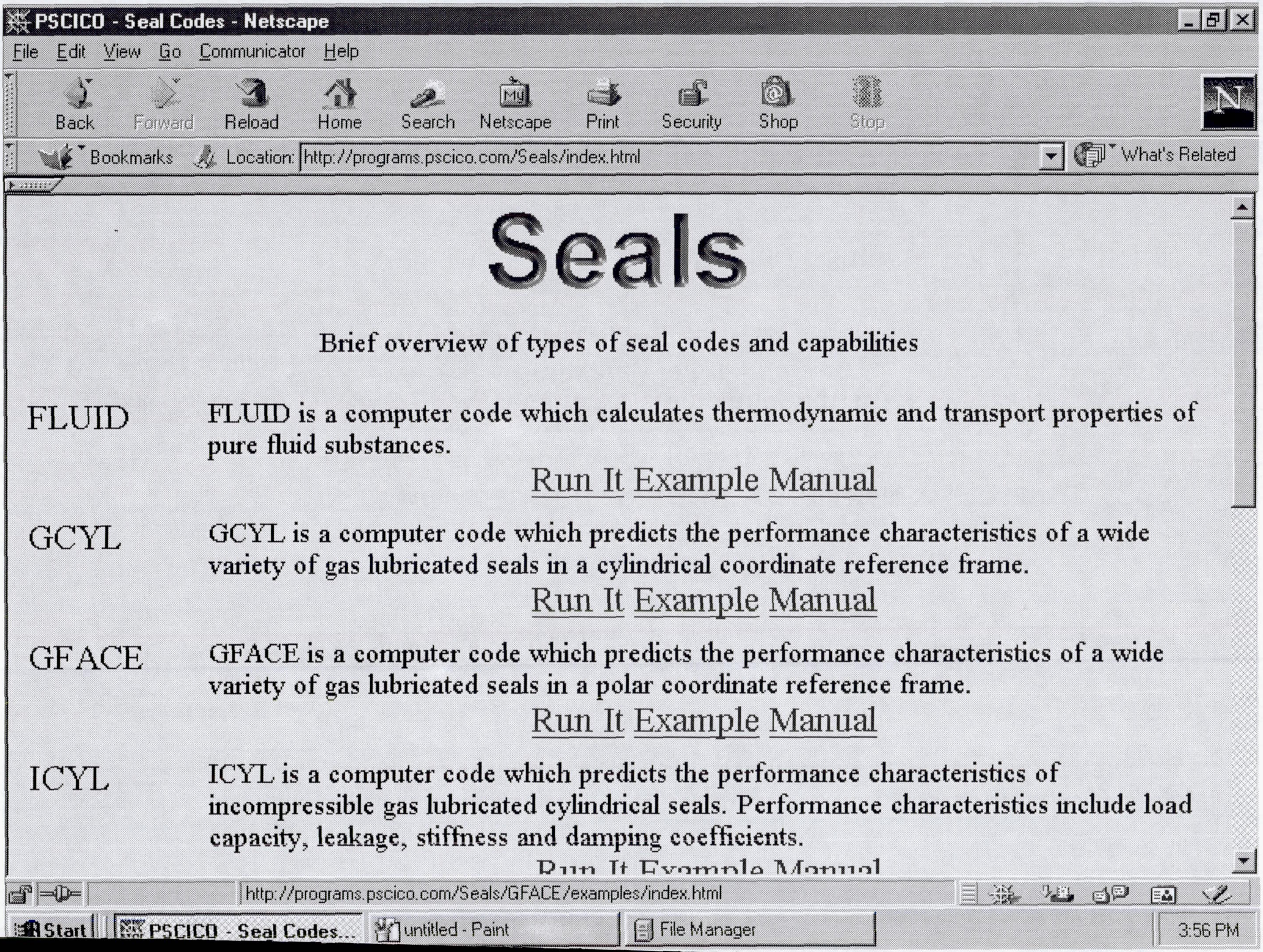
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Bookmarks Location: http://programs.pscico.com/Seals/index.html
What's Related
Seals
Brief overview of types of seal codes and capabilities
FLUID
FLUID is a computer code which calculates thermodynamic and transport properties of pure fluid substances.
Run It Example Manual
GCYL
GCYL is a computer code which predicts the performance characteristics of a wide variety of gas lubricated seals in a cylindrical coordinate reference frame.
Run It Example Manual
GFACE
GFACE is a computer code which predicts the performance characteristics of a wide variety of gas lubricated seals in a polar coordinate reference frame.
Run It Example Manual
ICYL
ICYL is a computer code which predicts the performance characteristics of incompressible gas lubricated cylindrical seals. Performance characteristics include load capacity, leakage, stiffness and damping coefficients.
http://programs.pscico.com/Seals/GFACE/examples/index.html
Start
PSCICO - Seal Codes...
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GFACE EXAMPLE DATA FILES

Recess Seal

Inside Radial Tapered Land

Rayleigh Step Seal Example #1

Single Tapered Land Seal 2B

Single Tapered Land Seal 2C

Recess Seal

Hydrostatis Source Seal

Control Parameters - Netscape

File Edit View Go Communicator Help

Control Parameters

Filename:

REC1

Description of Analyais: ***(TITLE)***

RECESS SEAL

Load or Clearance Option: ***OPTION = 1 OR 2***

- (•) **Calculate loads and moments, use provides shaft clearance and misalignment**
- ( ) **Calculate clearance, user provides load and initial clearance estimate**

Units: ***(UNIT)***

- (•) **English**
- ( ) **SI**

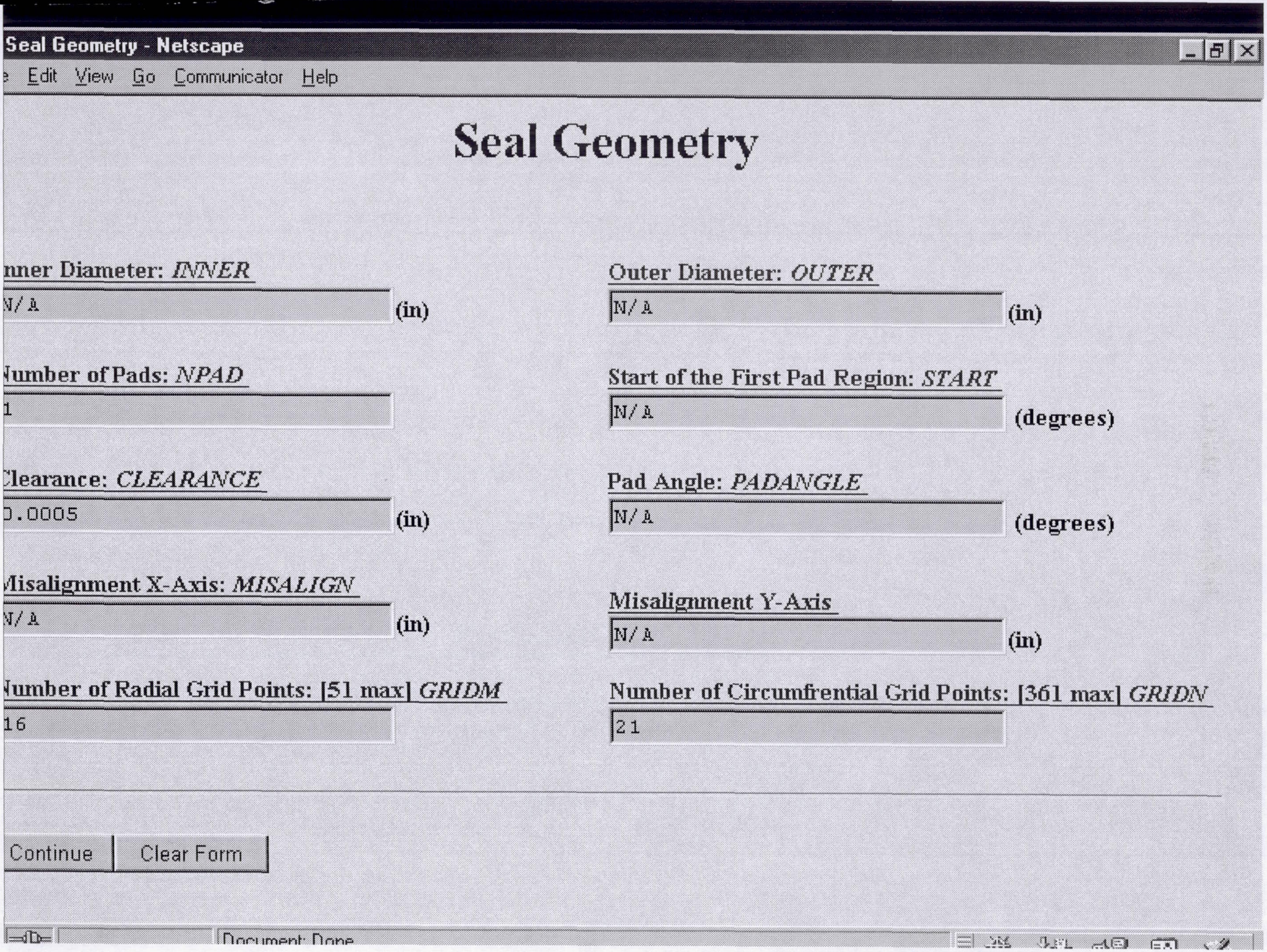
Grid:

- ( ) **Uniform**
- (•) **Variable**

BOUNDARY CONDITIONS:

- [ ] **Periodic** ***(JOINED)***

Document: Done


Seal Geometry - Netscape

e Edit View Go Communicator Help

Seal Geometry

nner Diameter: *INNER*
N/A (in)

Outer Diameter: *OUTER*
N/A (in)

Jumber of Pads: *NPAD*
1

Start of the First Pad Region: *START*
N/A (degrees)

Clearance: *CLEARANCE*
0.0005 (in)

Pad Angle: *PADANGLE*
N/A (degrees)

Misalignment X-Axis: *MISALIGN*
N/A (in)

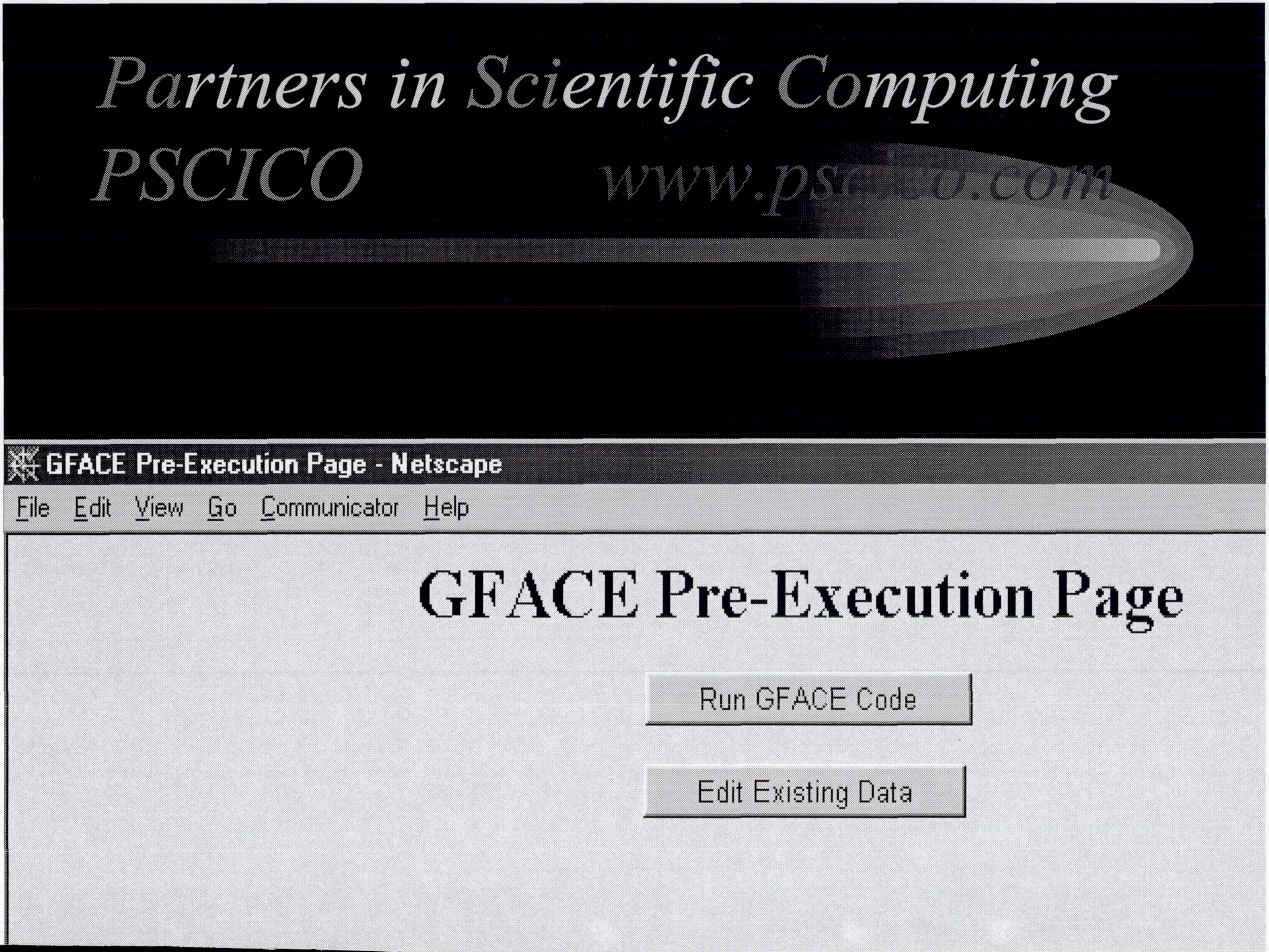
Misalignment Y-Axis
N/A (in)

Jumber of Radial Grid Points: [51 max] *GRIDM*
16

Number of Circumfrential Grid Points: [361 max] *GRIDN*
21

Continue | Clear Form

Document: Done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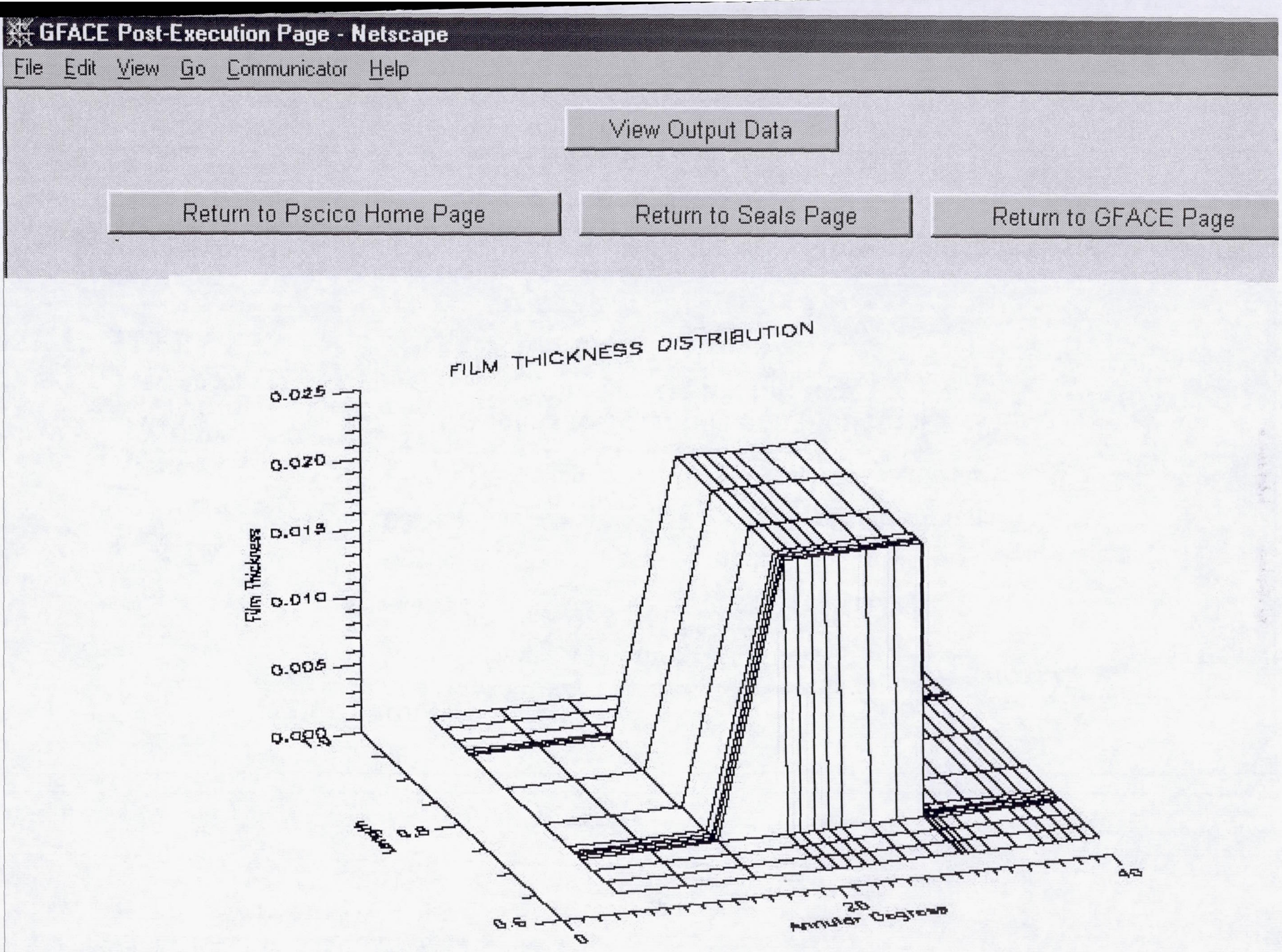
GFACE Post-Execution Page - Netscape
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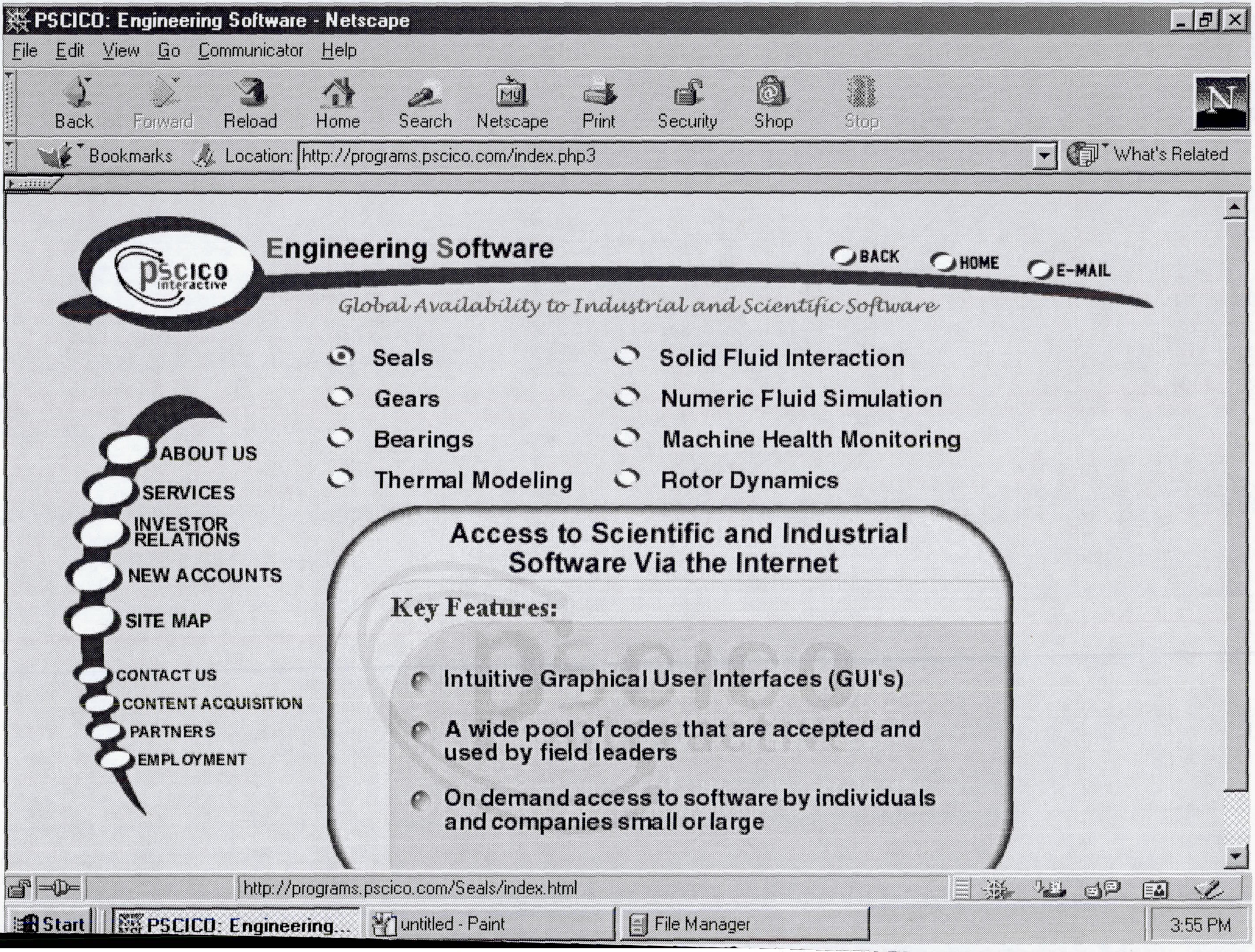
View Output Data
Return to Pscico Home Page
Return to Seals Page
Return to GFACE Page
FILM THICKNESS DISTRIBUTION
0.025
0.020
0.015
0.010
0.005
Film Thickness
0.8
0.6
0
20
40
Annular Degrees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Access to Scientific and Industrial Software Via the Internet
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A wide pool of codes that are accepted and used by field leaders
On demand access to software by individuals and companies small or large
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Start PSCICO: Engineering... untitled - Paint File Manager 3:55 PM

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Bookmarks Location: http://programs.pscico.com/Gears/GEARDYN/example1pinion.html What's Related

View / Edit Data File

NOTE: Input Data Format

*** Please note that the contents of this file is for display only. ***

Filename: planetg **Description:** Gear used in the examples

Gear Type: **Spur**

Number of Teeth: 30

Pressure Angle: 20 degrees
(If Pressure Angle is Zero, Enter Next Two Variables)

Pressure Angle at Drive Side: 0.0 degrees

Pressure Angle at Coast Side: 0.0 degrees

Outside Diameter: 4.025 in

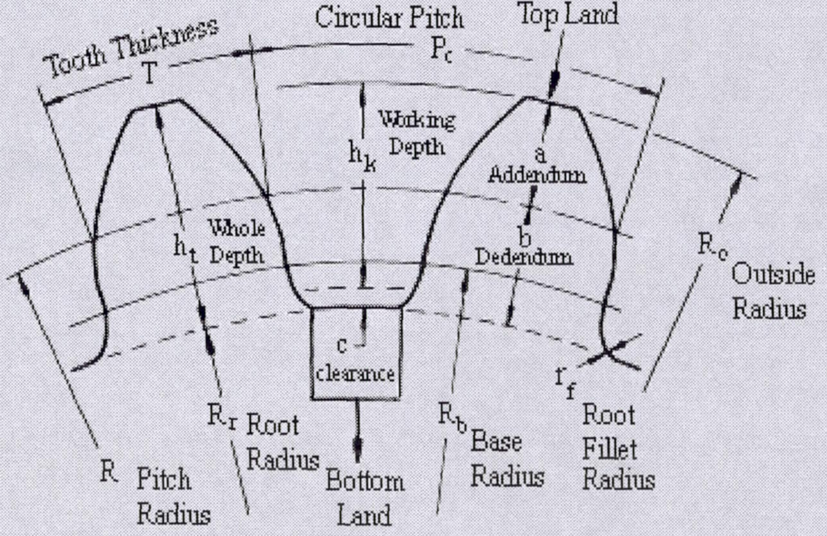
Inside Diameter: 0.0 in
(for internal type of gear)

Diametral Pitch: 8.0 in^{-1}

Gear Tooth Data

Face Width: 2.82 in

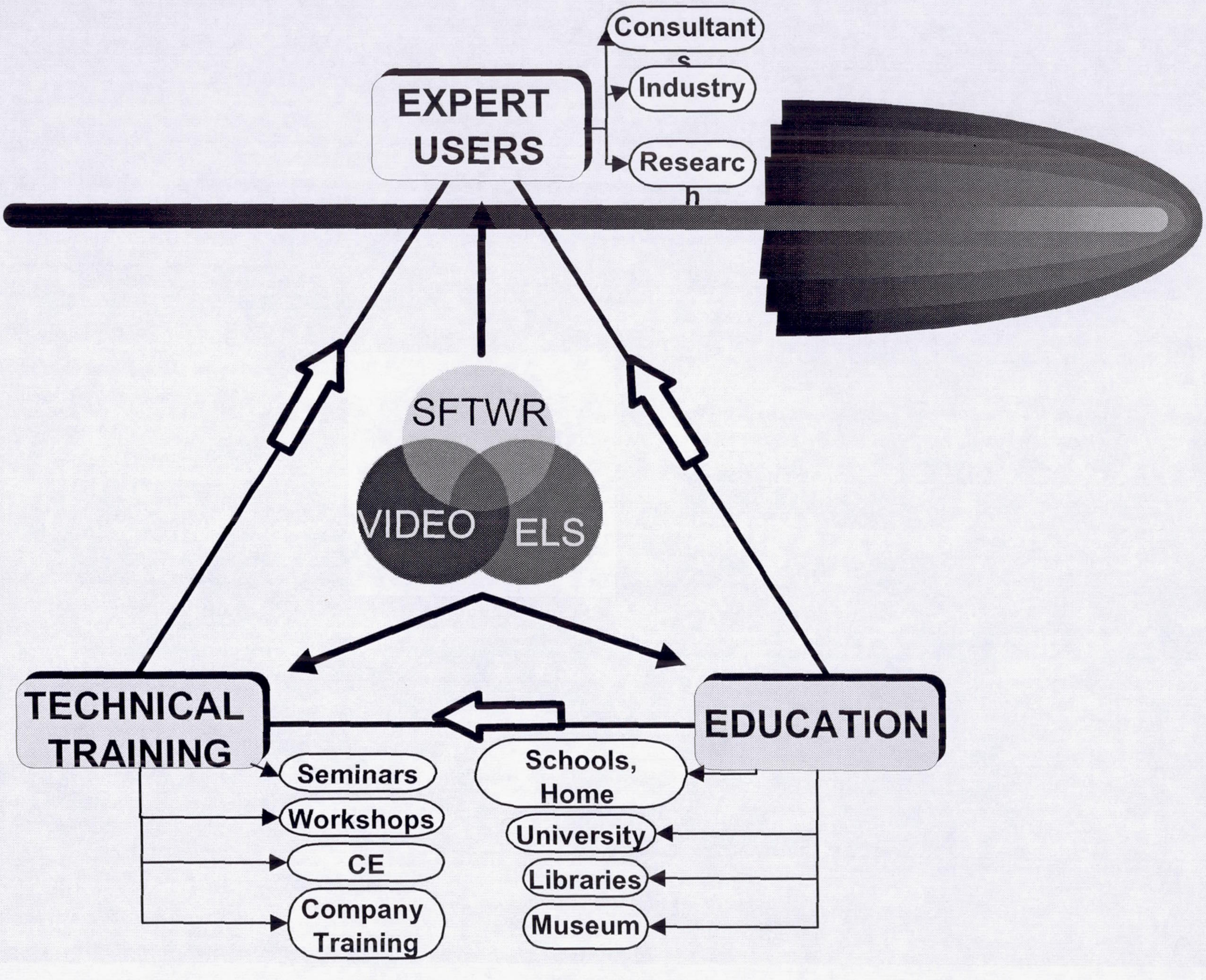
Fillet Radius, Maximum: 0.05 in



Basic Gear Geometry

The output files of GEARDYN program are:

Run-Time Text Output	Text	
Gear Tooth Load for Sun-Planet Mesh	Text	Plot
Gear Tooth Load for Planet-Ring Mesh	Text	Plot
Pressure * Sliding Velocity (PV) for Sun-Planet Mesh	Text	Plot
Pressure * Sliding Velocity (PV) for Planet-Ring Mesh	Text	Plot
Flash Temperature for Sun-Planet Mesh	Text	Plot
Flash Temperature for Planet-Ring Mesh	Text	Plot
Hertz (Contact) Stress for Sun-Planet Mesh	Text	Plot
Hertz (Contact) Stress for Planet-Ring Mesh	Text	Plot
Heywood (Bending) Stress on Planet Gear Tooth for Planet-Ring Mesh	Text	Plot
Heywood (Bending) Stress on Ring Gear Tooth for Planet-Ring Mesh	Text	Plot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THE TRAILBLAZER PROGRAM

Charles J. Trefny
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio

Glenn
Research
Center

The Trailblazer Program

Charles J. Trefny
NASA Glenn Research Center

NASA Seal/Secondary Air Workshop
October 28-29, 1999

Abstract

The NASA Glenn Research Center is developing Rocket-Based Combined-Cycle (RBCC) propulsion technology for application to reusable launch vehicles in its "Trailblazer" program. This presentation will explain the cost reduction potential of RBCC propulsion, highlight the major technical issues, and describe the elements of the Trailblazer program.

"Three Pillars for Success"

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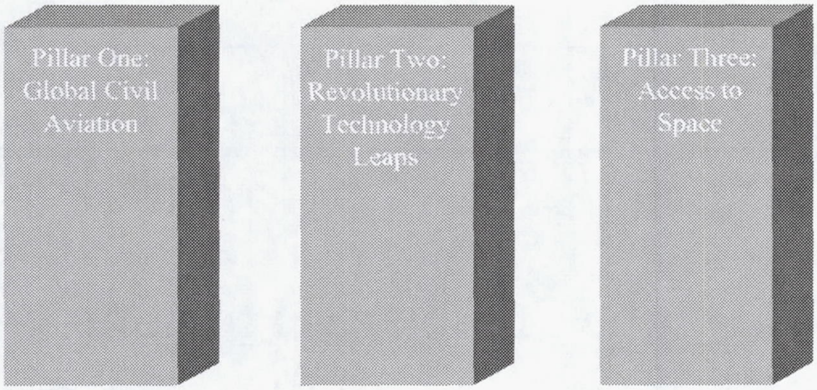
Established in 1997 by the
Office of Aeronautics and Space Transportation Technology (OASTT)
NASA Headquarters, Washington D.C.



An active area of hypersonic propulsion research at Lewis is the application of air-breathing propulsion to launch vehicles in order to reduce the cost of space access. "Three Pillars for Success" were established in 1997 by NASA's Office of Aeronautics and Space Transportation Technology (OASTT) in Washington D.C. Pillar three, Access to Space, set forth the goal of reducing the cost of space access.

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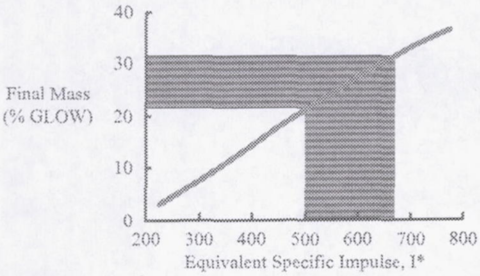
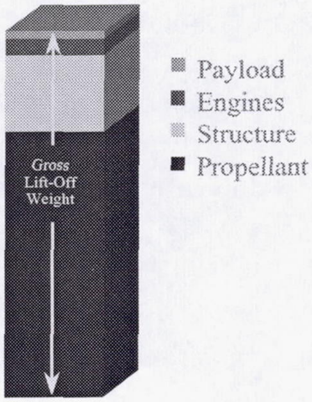
Potential for Reusability

RBCC propulsion provides the potential for reusable SSTO by reducing the fraction of propellant required





As depicted in the figure, RBCC propulsion can increase the structural mass budget, and thereby the potential for a more robust, reusable vehicle design. The range of I* values expected is from 500 to 650. The potential for greater reusability can only be realized however, if a number of mitigating factors related to the use of air-breathing propulsion can be effectively managed.

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Factors Mitigating RBCC Performance

- Weight and complexity of added propulsion components
- Burden of high speed flight within the atmosphere on the vehicle
- Increased fraction of low density hydrogen propellant

Increased I* or "aerothermodynamic" performance is offset by a number of mitigating factors. First, the RBCC engine will be somewhat more complex, and will weigh more than a rocket engine. To provide sufficient thrust for acceleration during the high-efficiency ramjet phase, the air flowpath must be of large cross-section with respect to the vehicle. It is also required that the inlet throat area be varied. The weight and complexity associated with these factors must be minimized by the RBCC designer. A second mitigating factor is the burden of high speed flight within the atmosphere on the vehicle. To accrue the I_{sp} efficiency benefit, the vehicle must fly a much lower altitude trajectory than a rocket-propelled vehicle. The effect of resulting high structural and thermal loads on structural weight must be minimized. Another system-level factor working to offset RBCC efficiency is a reduction in the propellant bulk density due to increased reliance on low-density hydrogen fuel. In ramjet and scramjet phases, only hydrogen is used. Increasing propellant volume results in increasing propellant tank weight, and vehicle drag.

The "Trailblazer" Program

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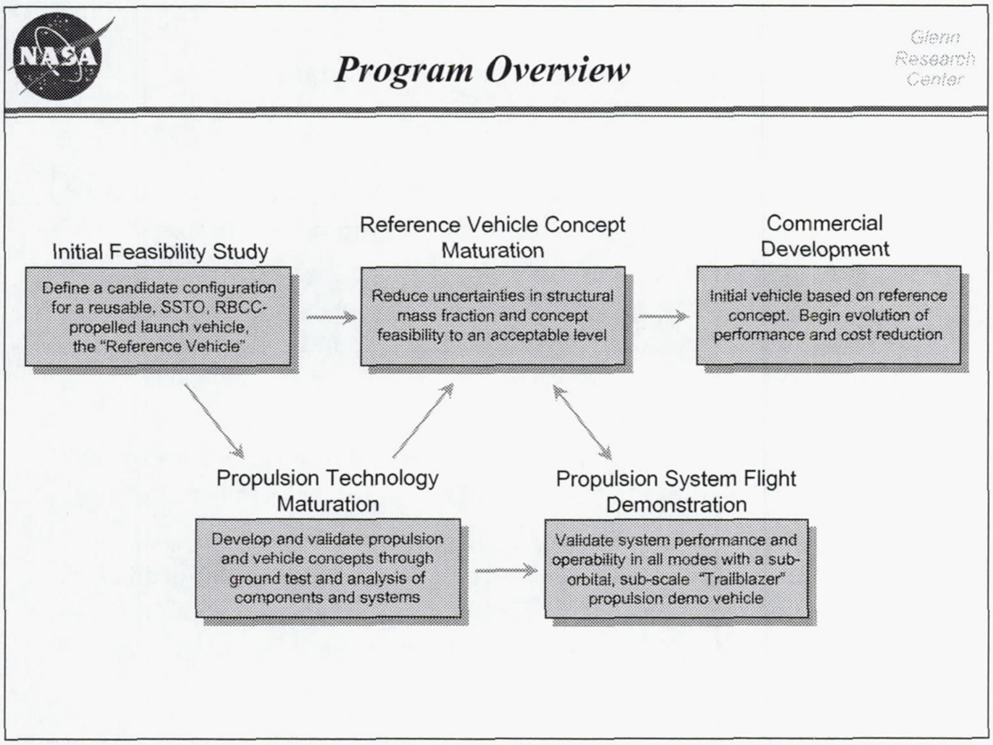
- "Trailblazer" is a reusable, SSTO launch vehicle concept, intended to reduce the cost of space access by making optimum use of air-breathing propulsion
- Development is based on maturation of a specific 300# payload "Reference Vehicle" configuration
- An objective of the program is to *manufacture* and *fly* a sub-scale, sub-orbital X-vehicle to demonstrate *system* performance goals
- Experiments and analysis are currently underway to mature the technologies required for this demonstration, and subsequent application of RBCC engine technology to the third pillar goals



The program began in 1996 with an initial feasibility study. This study defined a preliminary concept and indicated that the application of air-breathing propulsion to a reusable, single-stage-to-orbit, vertical lift-off launch vehicle warranted further study. The initial configuration was used to begin a multi-disciplinary, iterative process to mature the concept through experiments, numerical simulation and system optimization. Once a sufficient level of technical maturity is attained, a sub-scale, sub-orbital flight vehicle that represents the evolved concept will be manufactured and flight tested. All propulsion modes and transitions along the air-breathing trajectory will be demonstrated and an accurate assessment of the reference vehicle structural mass fraction will be possible. The successful completion of this program would allow the commercial development of a vehicle based on the reference concept. Then, through continued evolution in many fields including propulsion, structural design, materials, and multi-discplinary optimization, NASA will approach its third pillar goal of a ten-fold reduction in the cost of space access.

Trailblazer Reference Vehicle Characteristics

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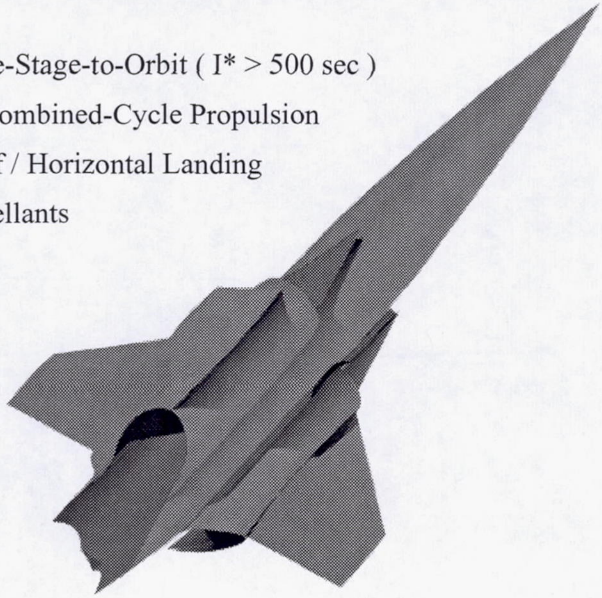
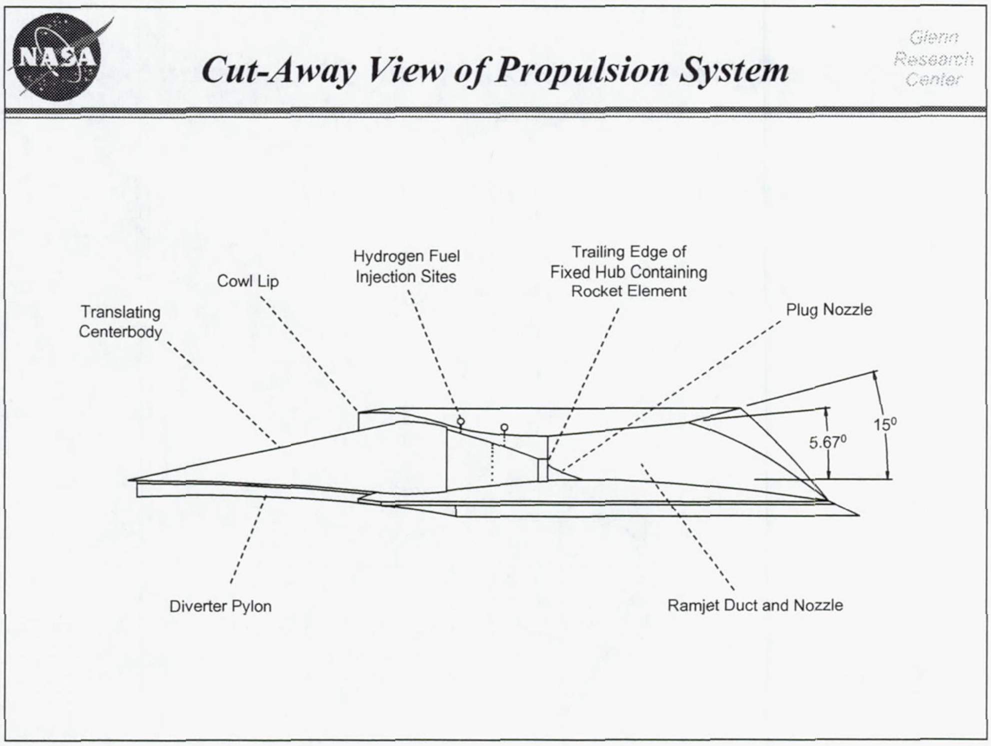
- Reusable, Single-Stage-to-Orbit (I* > 500 sec)
- Rocket-Based Combined-Cycle Propulsion
- Vertical Lift-Off / Horizontal Landing
- LOX/LH2 Propellants
- 300# Payload



The Trailblazer reference vehicle is a reusable, single-stage-to-orbit concept intended to take advantage of air-breathing cycle performance while minimizing the negative impacts of additional components, higher complexity, and flight within the atmosphere. The axi-symmetric architecture is intended to maximize the potential for structural and volumetric efficiency, and to reduce design and analysis uncertainty.

The vehicle is designed for vertical lift-off, and unpowered horizontal landing to minimize the weight associated with landing gear and wings. Safety and structural issues associated with high-speed taxi are eliminated by VTO. A by-product of VTO is a minimization of time spent in the atmosphere and therefore total heat load to the vehicle due to the high thrust-to-weight ratio required. A small-payload class is appropriate for air-breathing SSTO development. Scaling to large payloads can be accomplished without regard to runway length and load limits.

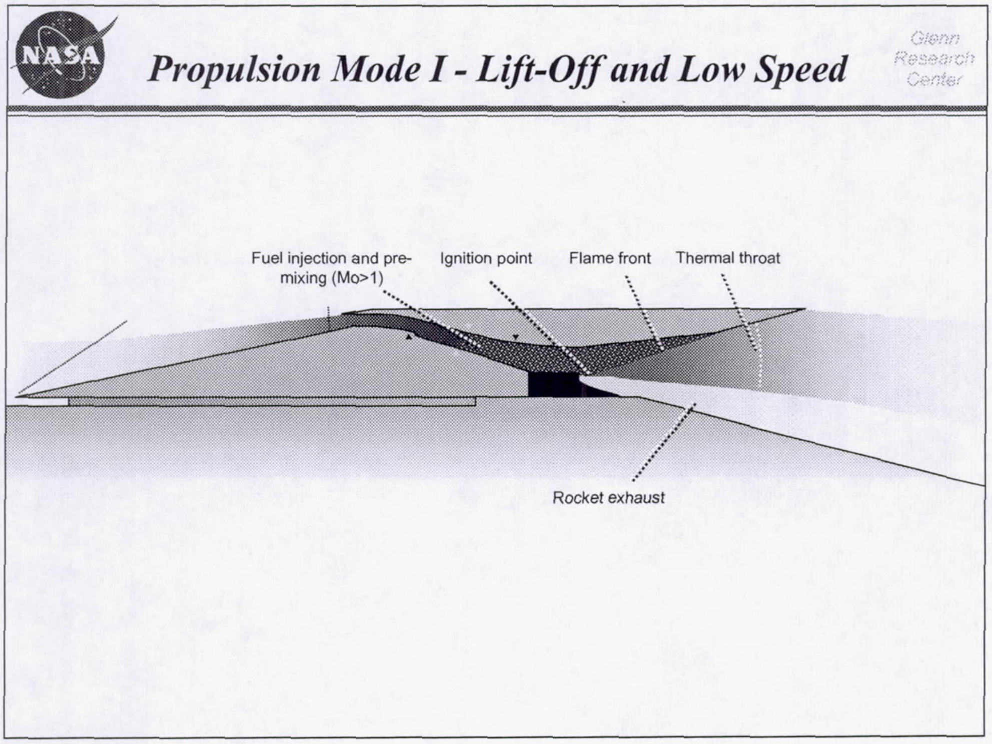
Liquid oxygen and liquid hydrogen propellants (LOX/LH2) are used. The cooling capacity and energy per unit weight of hydrogen are required. Hydrogen is also an ideal fuel from the standpoint of ignition, and flame stabilization due to its high flame speed. A drawback of hydrogen is its low density which results in structural weight and drag penalties.



The flowpath cross-section is an axi-symmetric sector with its axis on the boundary-layer diverter radius. Primary considerations leading to the choice of this geometry over a 2-D planar design are structural efficiency, simplicity in sealing and actuation, and design and analysis risk. As opposed to fully axi-symmetric designs, the centerbody is more easily supported and the nozzle is more easily integrated with the vehicle. The flowpath cross-section is not strictly axi-symmetric since the endwalls are not radial planes of symmetry.

A translating centerbody provides the required area variation. Fully-forward, it provides a maximum throat area and efficient spillage for low speed operation. In the aftmost position, it completely closes-off the flowpath for high area ratio rocket-mode operation. Intermediate positions are set for optimum inlet contraction ratio. Existing design and analysis tools for mixed-compression, axi-symmetric inlets have been used to generate the inlet contours. The maximum duct cross-section is sized to accomodate Mach 2 combustion in ramjet mode. See AIAA 99-2239 for further details.

Based on consideration of weight, simplicity, and reliability, each flowpath contains only one rocket element. This element is mounted in a hub that is fixed to the vehicle. The low speed cycle under consideration does not require that the air and rocket streams mix. The rocket operates at a fixed O/F and variable chamber pressure. The single rocket approach also results in better rocket-mode performance than multiple element designs.



At lift-off, the open inlet ventilates the duct to prevent overexpansion of the rocket. Below Mach one, there is no benefit to fueling the air stream. As flight speed increases, the ram air is pre-mixed with hydrogen fuel in the inlet diffuser upstream of its confluence with the rocket. The rocket provides the ignition source, and the rate of flame propogation determines the length of duct required. At Mach 2 and above, the air stream is fueled to stoichiometric proportion. The constant O/F rocket can be throttled for optimal system performance without regard for ramjet fueling requirements. The compact, high thrust rocket cycle used exclusively for lift-off gives way to the more efficient ramjet cycle as flight speed increases.

The issues associated with this mode of operation are flashback to the injectors, and control of the thermal throat location. Radial variations in fuel distribution are being examined numerically and expermentally as a possible approach.

See AIAA 99-2393 for further discussion and a complete description of the cycle analysis method used.

Propulsion Modes II & III - Ram and Scramjet

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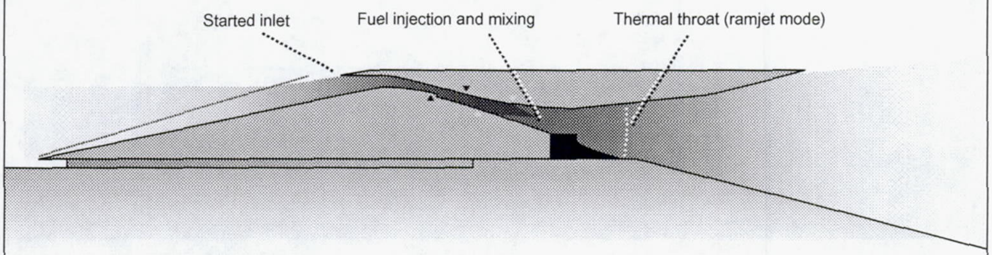
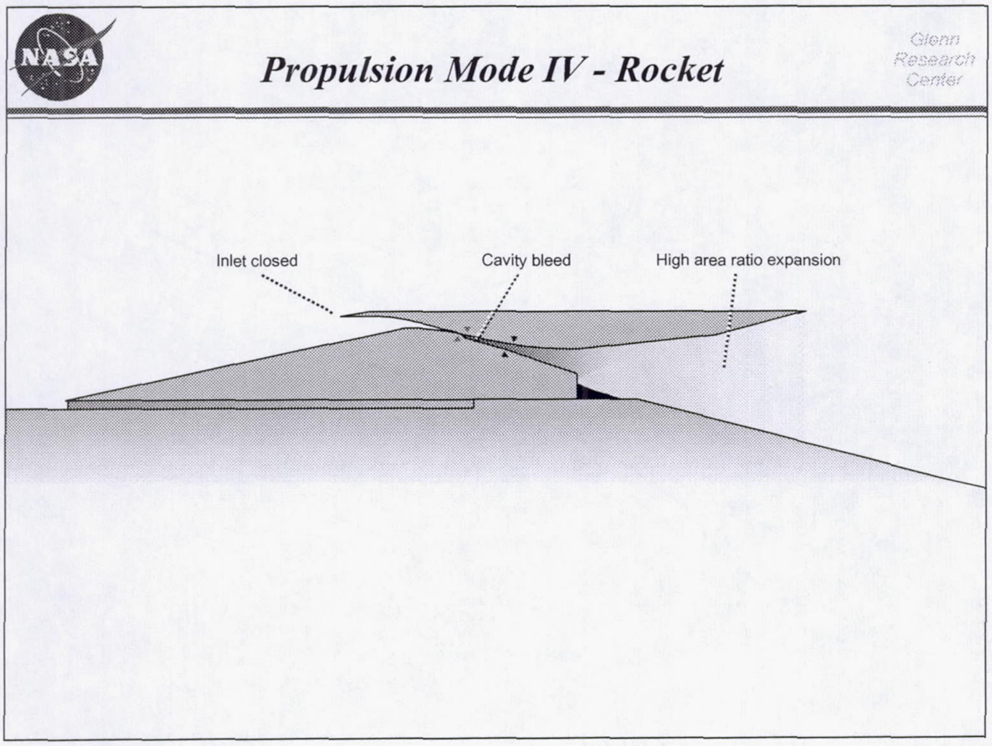


The ram and scramjet cycles operate in the traditional manner. The inlet is started in these modes. A large thermal throat area is required for efficient ramjet mode operation at low Flight Mach numbers. Although the duct cross-section is sized accordingly, fuel distribution and flameholding in the large cross-section are an issue. Pre-mixed operation is being examined as possible solution in the propulsion technology maturation effort.



Mode IVis a high area ratio rocket, taking advantage of the 400:1 area ratio between the vehicle projected area and rocket element throat. A portion of this area ratio is necessarily free-expansion however. The impingement of the plume on the flowpath surface is managed using a small amount of cavity bleed. System performance is very sensitive to mode IV Isp, since this mode accounts for over 50% of the total ΔV.

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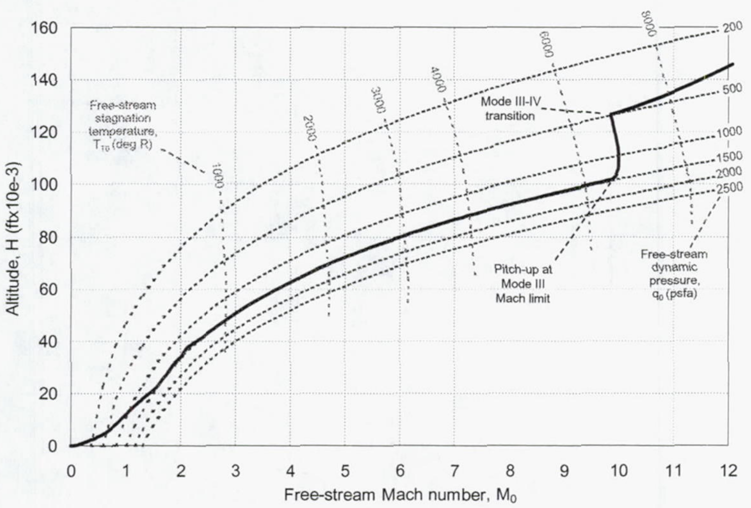
Optimal Trajectory



The air-breathing portion of the trajectory is characterized by acceleration at the constrained maximum dynamic pressure of 1500 psfa to the constrained maximum air-breathing Mach number of 10. The vehicle then climbs at constant Mach number to the constrained minimum dynamic pressure of 500 psfa at which point transition to rocket mode occurs. The remainder of mode IV, the coast phase, and the circularization burn are not shown.

Effective Isp and therefore I* tend to increase with vehicle thrust-to-weight ratio. This is why the optimal trajectory tends toward the maximum allowable dynamic pressure.

Inlet Development and Validation (Rig 2)

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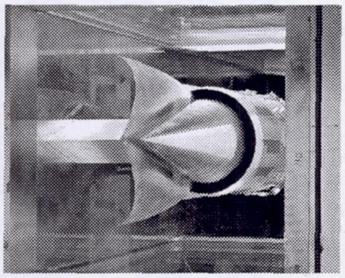


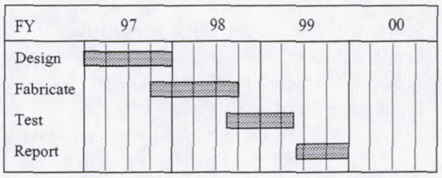
Objectives

- Determine performance of bleedless design from Mach 2.5 to 6
- Determine maximum contraction ratios and back-pressures
- Assess validity of 2-D (axisymmetric) calculated performance
- Acquire data for comparison to 3-D FNS calculations

Description

Scale: 5% of 130,000# ref veh (2.65" R_c)
Facility: LeRC 1x1 Supersonic Wind Tunnel
Test cond: Mach 2.5-6.0 (aerodynamic)
Features: Actuated centerbody and flow plug
Cold-pipe mass flow measurement
Static, pitot, and dynamic pressures

Schedule



Point of Contact: Charles.J.Trefny@GRC.NASA.gov

Forebody-Inlet Integration (Rig 3.1)

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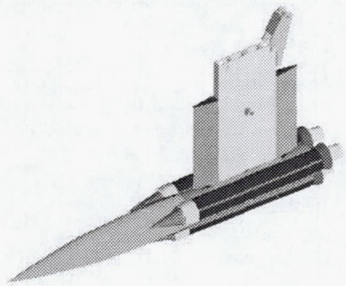


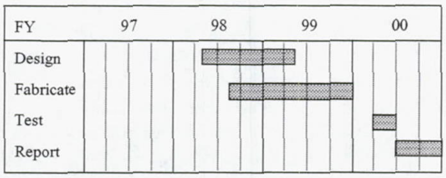
Objectives

- Determine effects of AOA on mass capture and inlet operability
- Assess effectiveness of, and need for boundary layer diverters
- Determine the severity and effects of pod-to-pod and pod-to-body shock interactions
- Validate 3-D FNS CFD calculations

Description

Scale: 13% of 130,000# ref. vehicle
Facility: GRC 10'x10' Supersonic W/T
Test cond: Mach 2.0-3.5, Alpha +/-9°
Features: Fixed inlets (phase 1)
Removable boundary layer diverters
Inlet mass flow rate measurements
Oil flow, press sens paint, laser sheet

Schedule



Point of Contact: Hyun.D.Kim@GRC.NASA.gov

Rocket Element Development (Rig 6)

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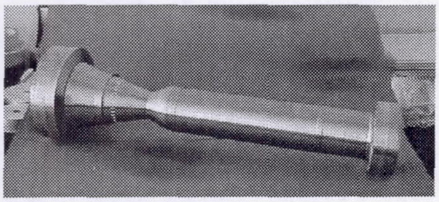


Rig 1 Rocket During Fabrication

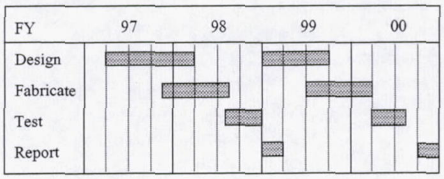
Objectives

- Mutiple projects for rocket element maturation
- Develop rocket element for use in Rig 1 testing
- Quantify performance and heat transfer characteristics
- Subscale development of internal semi- annular rocket
- Subscale evaluation of rocket injector element designs and chamber cooling configurations for use in full scale engine.

Description

Scale: Variable
Facility: GRC CRL32
Test cond: $P_c < 1200$ psia; O/F 3-7; 2000# Thrust
Features: Oxygen and Hydrogen propellants
Water or liquid hydrogen cooling
High speed and dynamic data

Schedule



Point of Contact: Timothy.D.Smith@grc.nasa.gov

Direct-Connect Mixer/Combustor (Rig 1)

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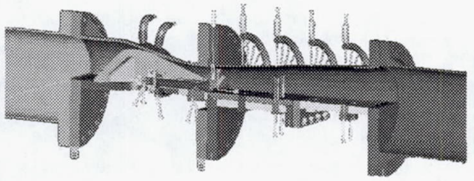


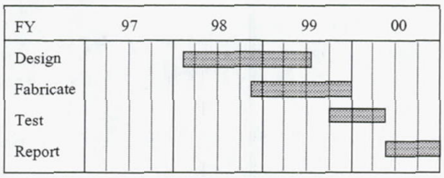
Objectives

- Evaluate performance and operability of both the SMC and IRS mode 1cycles
- Determine the combustor length required for both mode 1 cycle options
- Demonstrate transition from mode 1 to 2, and develop mode 2 fuel injection and flameholding strategy
- Evaluate performance of internal nozzle in mode 4
- Evaluate actively-cooled, flight-weight flowpath segments

Description

Scale: 20% of 130,000# ref vehicle
Facility: GRC ECRL
Test cond: SLS to Mach 3 (true temperature)
Features: Gaseous H2/O2 rocket
Variable combustor length
Movable centerbody
Various fuel injectors and stations

Schedule



Point of Contact: Scott.Thomas@GRC.NASA.gov

Integrated Propulsion System Pod (Rig 4)

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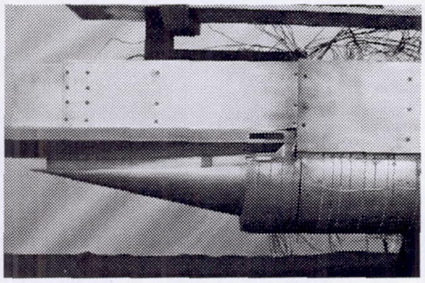


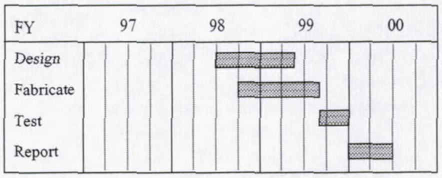
Objectives

- Develop and optimize ram and scram mode fuel injection scheme in the presence of realistic inlet flow profiles
- Determine uninstalled performance from Mach 3.4 to 7
- Establish maximum inlet contraction over a range of temperatures and Re #
- Assess effects of test flow vitiation on engine performance

Description

Scale: 10% of 130,000# ref veh (5.13" R_c)
Facility: GASL L4 and GRC Plum Brook HTF
Test cond: Mach 3.4 - 7 (true temperature)
Features: Actuated centerbody
Parametric copper heat sink design
Multiple fuel injection stations
Thrust, static and pitot pressures, wall temperaturess; skin friction

Schedule



Point of Contact: Scott.Thomas@GRC.NASA.gov

Nozzle Performance (Rig 8)

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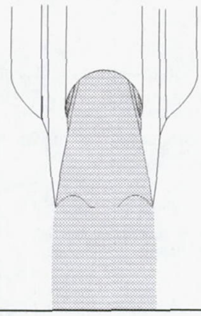


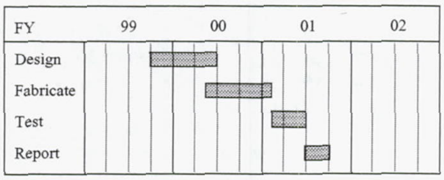
Objectives

- Provide experimental assessment of losses due to under/over expansion, flow divergence, shocks, and base drag for inclusion into a performance model
- Determine effect of secondary flow on mode IV expansion process efficiency

Description

Scale: TBD
Facility: GRC 8x6, Vacuum chamber
Test cond: SLS, Mach .8-2, Vacuum
Features: Dual warm flows simulate rocket and air streams (IRS cycle)
Variable air stream throat area
Single-component force balance

Schedule



Point of Contact: Charles.Trefny@grc.nasa.gov

Rocket-in-a-Duct Code Validation (Rig 7)

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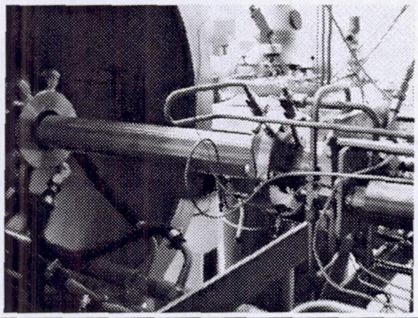


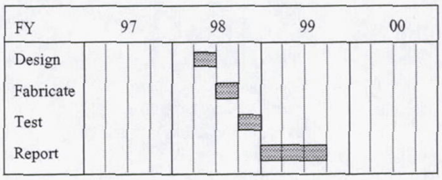
Objectives

- Develop generic expansion efficiency model
- Measure performance of rocket-in-a-duct
- Evaluate geometry with FNS-CFD
- Validate axisymmetric, FNS results

Description

Scale: 1/500
Facility: RCL-11
Test cond: GH/GO, MR=4, Pc=100 psia
Features: Altitude Test, +/-1% Thrust

Schedule



Point of Contact: Steven.Schneider@grc.nasa.gov

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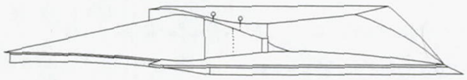
Flight-Like Integrated Propulsion Sys. (Rig 5)



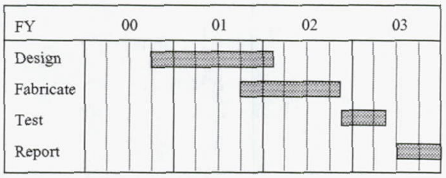
Objectives

- Demonstrate power-balanced operation in all operating modes
- Demonstrate closed-loop control of variable geometry and propellant flows
- Determine uninstalled performance in all operating modes
- Provide sufficient confidence to proceed with flight demonstration

Description

Scale: Largest practical
Facility: 10x10, HTF
Test cond: SLS, Mach 2-7
Features: Flight-like construction
Water or LH2 cooled
Remote centerbody actuation and fuel staging
Closed-loop control system

Schedule



Point of Contact: Charles.Trefny@GRC.NASA.gov

Basis for Structural Weight Estimates

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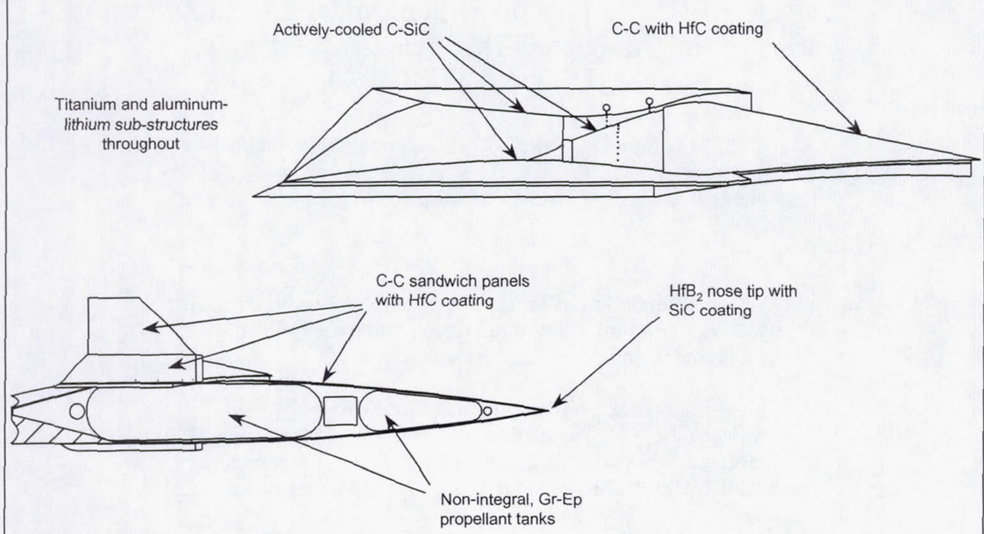

This chart presents an overview of materials assumptions used to arrive at a gross lift-of-weight of approximately 225,000 pounds. Technical challenges associated with manufacturing and coating actively-cooled composites are being addressed by a government-contractor team under a NASA NRA. This team will also further optimize structural architectures and examine various alternatives.

Pratt-Whitney NRA Activity

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ABLV RBCC Propulsion System Materials, Structures, and Integrated Thermal Management (NRA-98-LERC-2A)

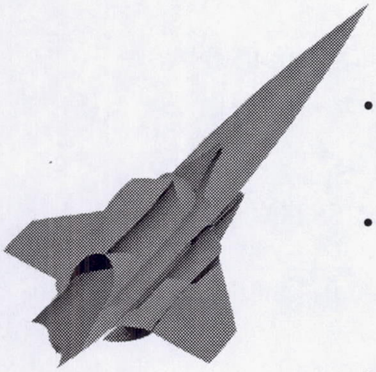
- 18 mo / $2M contract awarded to Pratt-Whitney September, 1999
- Complement to existing NASA in-house activity
- Products

    1) Recommendation of propulsion system architecture including the use of light-weight, high-temperature materials, thermal management, and propellant cycle design

    2) Estimate of the propulsion system flight-weight

    3) Recommendations of areas for further analysis or technology development that may lead to reduced weight or increased reusability

Flight Demo Vehicle Characteristics



- Geometrically, dynamically similar to the reference vehicle at about 1/2 scale
- 40% propellant mass fraction, required for single-flight, all-mode demonstration to 11000 fps
- Phased, envelope-expansion approach

Trailblazer Program Status

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- FY2000 Funding approximately $15M from the NASA Propulsion Base R&T program
- Included in the NASA Headquarters "Spaceliner 100" Roadmap as a candidate for hydrogen SSTO
- Participation by NASA Glenn, Marshall, Langley, and Dryden
- Other contractor and university efforts in-place

Summary

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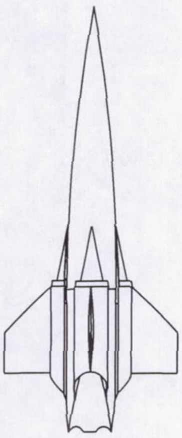

- "Trailblazer" is a reusable, SSTO launch vehicle concept, intended to reduce the cost of space access by making optimum use of air-breathing propulsion
- Propulsion component experiments and advanced analysis is underway to mature reference vehicle design
- A program objective is to flight demonstrate aeropropulsion performance, structural weight, reusability, and operability

INFLUENCE OF ROCKET ENGINE CHARACTERISTICS ON SHAFT SEAL TECHNOLOGY NEEDS

John E. Keba
Rocketdyne Division
Boeing North American, Inc.
Canoga Park, California

Influence of Rocket Engine Characteristics on Shaft Seal Technology Needs

John E. Keba
Rotating Machinery Analysis Group
Rocketdyne Division
Boeing North American, Inc.

NASA - Glenn Research Center
Seal/Secondary Air Delivery Workshop
October 29, 1999

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BOEING

Slide 1

Follow-on to last years presentation on "Rocket Turbomachinery Shaft Seals" which described the sealing technology challenges of Inter-Propellant Seal Systems and Lift-Off Seal Systems.

This presentation will highlight how the type of engine and mission influence shaft seal requirements.

The intent is to explain that rocket engine seal technology development plans need to focus not only on a particular type of seal system (IPS or Lift-Off), but they also need to be focused on a particular engine and mission type (application) as well. New engines need seal development programs.

Influence of Rocket Engine Characteristics on Shaft Seal Technology Needs

- **Introduction -- Rocket Turbomachinery Shaft Seals**
    - **Inter-Propellant-Seal (IPS) Systems**
    - **'Lift-off' Seal Systems**
    - **Technology Development Needs**
- **Rocket Engine Characteristics**
    - **Engine cycles, propellants, missions, etc.**
    - **Influence on shaft sealing requirements**
- **Conclusions**

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Slide 2

Introduction is quick review of IPS seals using SSME HPOTP seal as example, and Lift-off seals using SSME HPFTP lift-off seal as example. Areas where technology advancement is desirable are highlighted.

Rocket engines will then be be discussed, emphasizing how different characteristics - cycle type, propellant, mission etc -- drive seal requirements. Major point is there is much more diversity in the design of rocket turbopump seal systems than is generally appreciated.

Conclusion is that new propulsion systems for launch vehicles inevitably place new demands on shaft seal systems that are not adequately met with existing seal technology.

Inter-Propellant-Seal (IPS)

- IPS Purpose
  - Separate incompatible fluids
  - Limit propellant leakage

- Technology advancement needs
  - Reduction or elimination of buffer gas consumption
  - Reduce or eliminate drain requirements
  - Reduce length of seal system
  - Higher seal surface velocities

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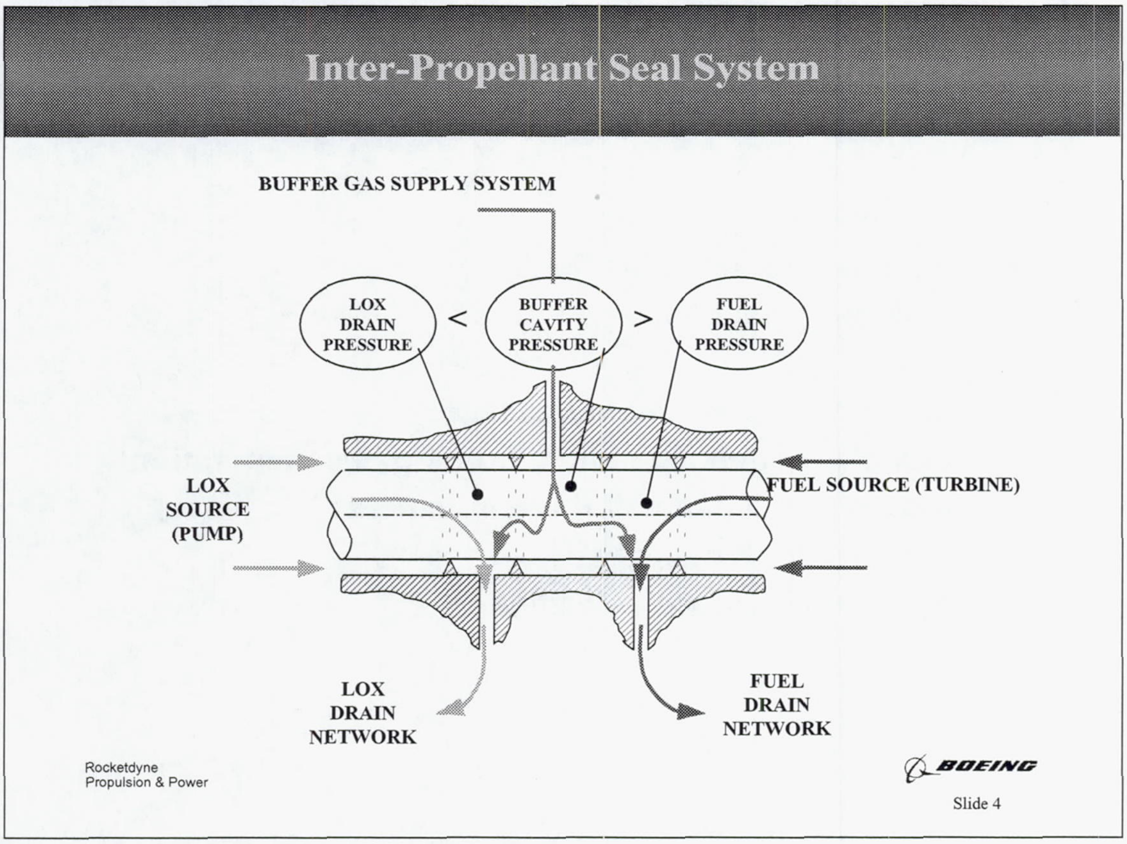
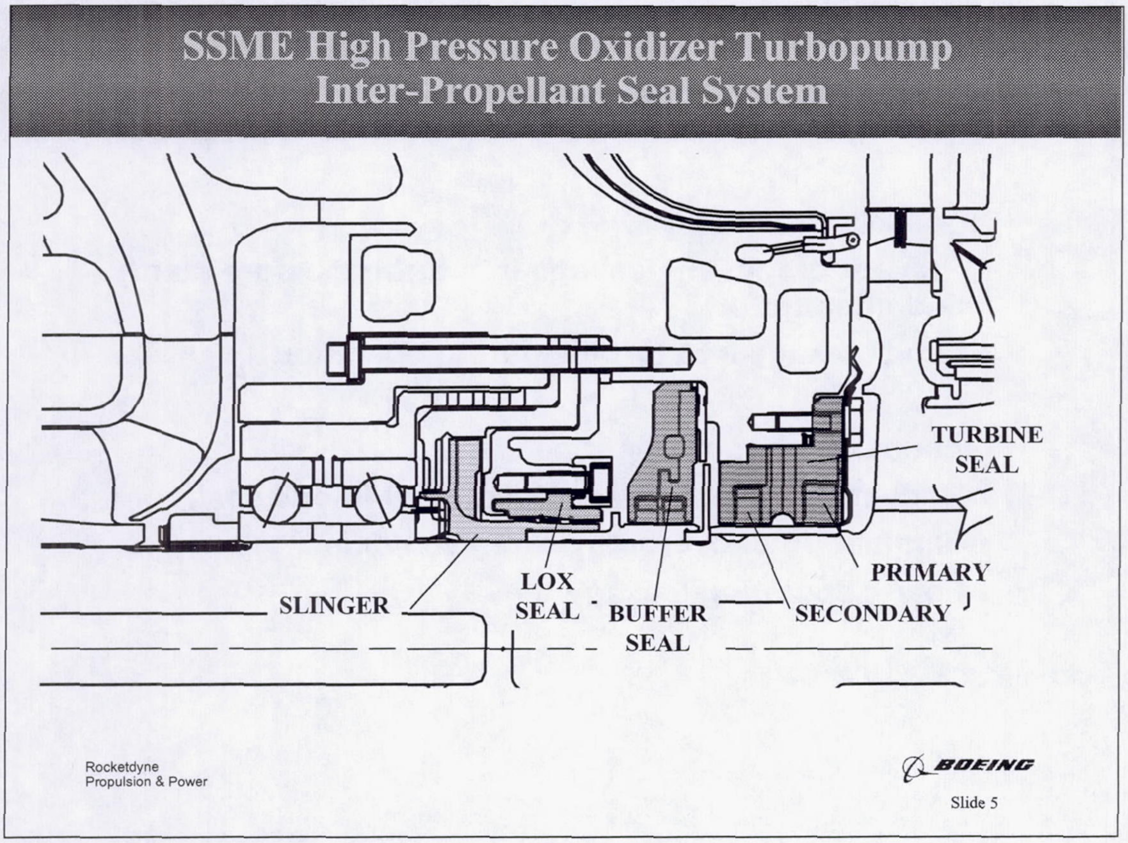
Slide 3

The fundamental purpose of the IPS is to keep the oxidizer and the fuel separate inside the turbopump. If they should mix inside the pump, it is likely that they will ignite causing a catastrophic failure of the engine. These seals are typically used between the pump and turbine in oxidizer turbopumps and, in single shaft turbopumps (pumps where both fuel and oxidizer are mounted on one shaft) between the fuel pump and oxidizer pump.



Schematic of a typical inter-propellant seal. There are generally at least three discrete seal components. An inert gas, helium, is used to provide a buffer zone between the two incompatible fluids. There are five subsystems in addition to the seals themselves which require equal attention in design -- the two sources, the two drains and the buffer gas supply. The basic operating requirement is the buffer cavity pressure is always maintained higher than either of the adjacent drain pressures.



Detail of the HPOTP inter-propellant seal package.

All seal are clearance type seals. LOX seal leakage is high during chill and at low power settings when the slinger does not vaporize the fluid. Turbine seal ΔP is about 3000 psi -- to high for many seal designs.

Very robust system but significant performance, size and weight penalty for low thrust engines.

Lift-off Seal System

- Purpose
  - Prevent propellant leakage into turbine before start and after cut-off
  - Limit leakage into turbine during operation

- Technology advancement needs
  - Reduction in seal system length (all-in-one seal)
  - Elimination of overboard drain/vent line
  - Lower operating leakage

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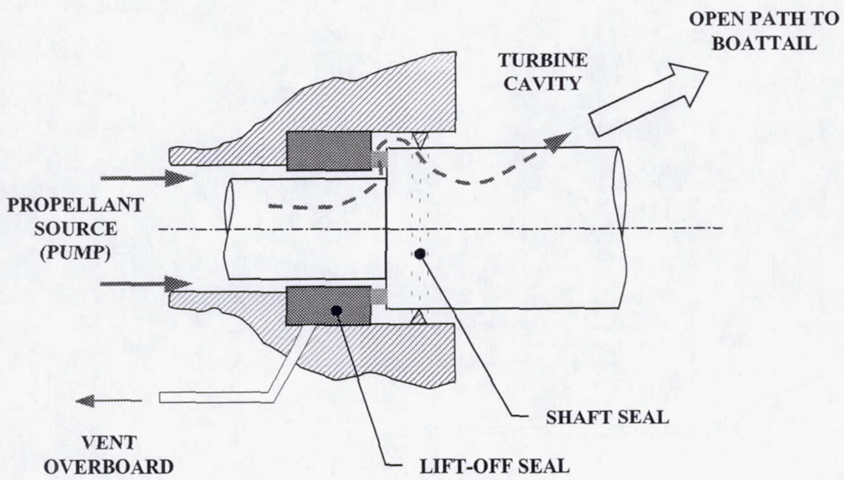
Lift-off seal: Rocketdyne's terminology for a shaft seal (generally face seal) which provides a contacting, very low leakage seal at zero or slow speed operation and opens fully during operation, providing negligible flow restriction.

A separate seal, typically a clearance type seal, is used in series with the lift-off seal to limit leakage during operation.

Long, complicated seal system. High speed capability face seals may provide significant improvement in some applications.

Lift-off Seal System



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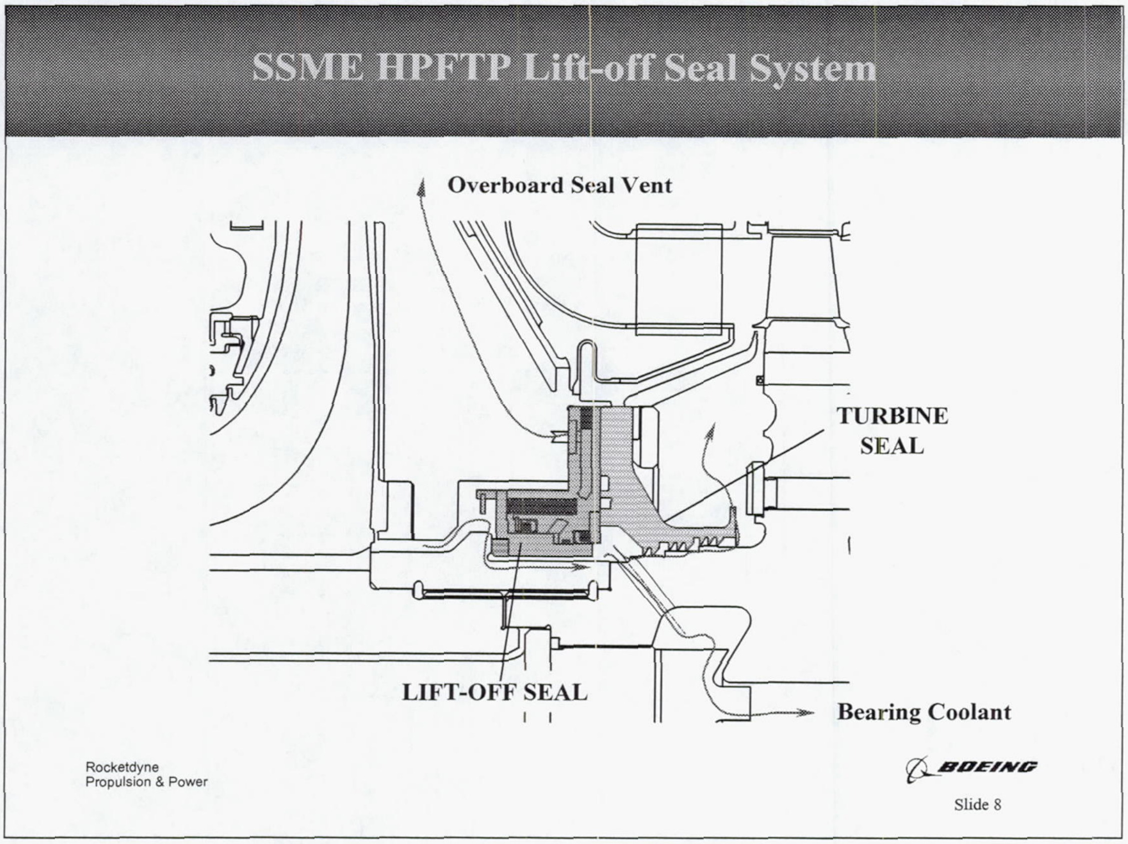
Schematic of lift-off seal. Leakage into turbine cavity has open path to nozzle. Problem with hydrogen during chill because difficult to dilute to safe concentration. Thermal condition of turbine also undesirable with cryogenic leakage. With storable fuels, leakage into turbine can also present problems.

Seal actuates open when rising pressure on upstream and/or downstream side cause pressure loading to overcome spring load. An overboard vent is usually necessary to provide low pressure on the back side of the carbon so that the seal stays open without a pressure drop across the nose.

Shaft seal provides the resistance to leakage after the lift-off seal opens, limiting propellant flow into the turbine.



SSME High Pressure Fuel Turbopump Lift-off seal and turbine shaft seal.

Lift-off seal prevents liquid hydrogen leakage into turbine during pump chilldown. During operation, Lift-off seal opens and leakage into turbine is limited by stepped labyrinth seal. Hole in shaft between Lift-off seal and labyrinth seal provides coolant flow to turbine end bearing.

Engine Characteristics

Rocket Engine Classifications

Engine Cycle

'Open' Cycle
- Gas Generator
- Expander

'Closed' Cycle
- Staged Combustion
  - Fuel Rich
  - LOX Rich
- Expander

Propellants

Cryogenic
- LOX -- LH2
- LOX -- Kerosene

Storable
- NTO -- MMH, UDMH, etc..
- H2O2 -- Kerosene

Vehicle

- Booster
- Upper Stage
- Single Stage-to-Orbit

Other

Expendable Vs. Reusable

Man Rated Vs Non-Man Rated

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Slide 9

Rocket engines can be classified in various ways -- by their thermodynamic cycle, by propellant combination, vehicle type or application and others. These engine characteristics combine into a large number of permutations and result in unique turbomachinery requirements for every application. Consequently, shaft seal systems generally have unique requirements for each engine.

Engine Cycle

Cycle defined by fluid source used to drive turbines

'Open' Cycle -- Turbine drive gas exhausted downstream of Main Combustion Chamber (MCC)

- Gas Generator Cycle -- Propellants burned (fuel rich) to drive turbine
- Expander Cycle -- Propellant is vaporized and heated by MCC or nozzle to drive turbine

Influence on shaft seals:

- Relatively low turbine cavity pressures
- Impulse turbine -- turbine flows affected by seal leakage

'Closed' Cycle

- Staged Combustion - Partial combustion of propellants, turbine exhausts into MCC injector head

Influence on shaft seals:

- Very high pressure in turbine cavity
- Relatively high turbine flow rate compared to seal leakage
- Very high pump pressures

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Slide 10

The cycle type most directly affects seal operating pressures and allowable leakage into or from the turbine cavity. This may determine the type of seal required -- clearance seals for high pressures or rubbing contact seals for minimum leakage.

Vehicle

- Booster
  - High thrust -- high propellant flowrates, large pumps
  - *Weight and performance less critical than upperstage and STO*
- Upper Stage
  - Low thrust -- low flowrates, small higher speed pumps
  - Restart requirement
  - Weight and performance critical
- STO
  - Wide throttle range, large pumps
  - Weight and performance very critical

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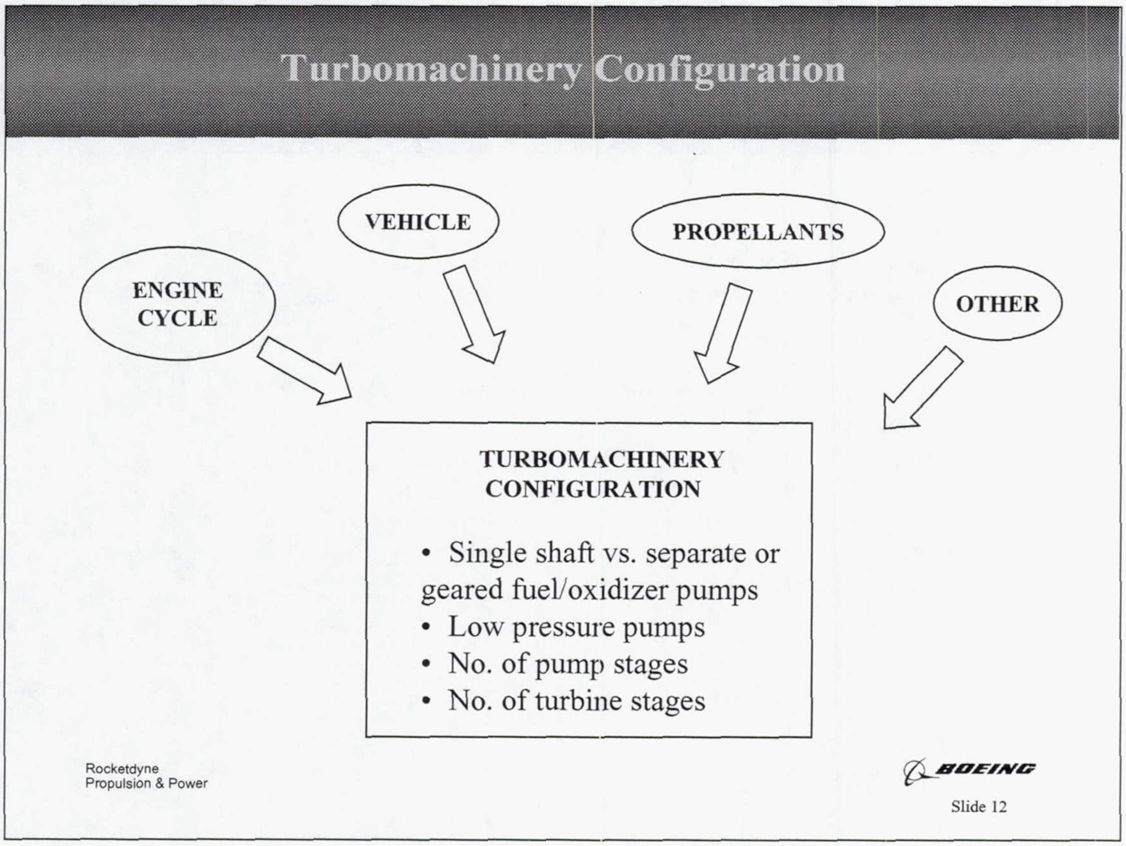
The vehicle or application generally defines the thrust class and performance level required. Boosters are generally large and shaft leakages are generally more of a safety and operability concern than a performance concern. Often, multiple engines are used for a booster stage. Overall engine performance is not as critical because the propulsion system is not carried to full orbital velocity.

Weight is more critical for the upperstage because it trades almost one-to-one with payload weight. Therefore the importance of seal system performance increases relative to that of other trade factors.

STO combines the requirements of booster and upper stage, often adding the additional requirement of reusability.



Turbomachinery Configuration covers the number of turbopumps and the basic layout of the individual turbopumps -- whether pump inducers are needed, type of turbine, number of pump and turbine stages, approximate size and speed. The engine characteristics in conjunction with constraints on turbopump component capabilities set the turbomachinery configuration.

As examples:

- Differences in fuel density compared to oxidizer density generally determines if individual pumps are required.
- Propellant supply conditions(vehicle tanks) influence the need for separate low pressure pumps and effect turbopump speed selection.
- Propellants influence materials selection which impact component capabilities.
- Safety factors and life requirements are set by the application and impact component capabilities.

With the basic turbomachinery configuration set, seal system requirements are determined in concert with bearing design and rotordyamic analysis.

Engine Data Summary

Engine Cycle	Propellants	Engine Designation	Vehicle	Thrust	Turbomachinery Configuration
Gas Generator	LOX - RP1	F1	Booster - Saturn 5	1,500,000 SL	Single Shaft
	LOX - RP1	RS-27	Booster - Delta	200,000 SL	Geared
	LOX - LH2	Vulcain	Booster - Ariane 5	225,000 SL	Two Shaft
	LOX - LH2	HM7	Upper Stage - Ariane 4	14,000	Geared
	NTO - UH25	*Viking*	*Booster - Ariane 4*	*150,000 SL*	*Single Shaft*
	NTO - A50	LR-87	Booster - Titan	275,000 Vac	Geared
	NTO - A50	LR-91	Upper Stage - Titan	100,000 Vac	Geared
Expander	LOX - LH2	RL-10	Upper Stage - various	25,000 Vac	Geared
	LOX - LH2	LE-5	Upper Stage - H2	27,000 Vac	Two Shaft
Staged Combustion - Fuel Rich	LOX - LH2	SSME	Booster - Space Shuttle	375,000 SL	2 HP and 2 LP
	LOX - LH2	*LE-7*	*Booster - H2*	*190,000 SL*	*Two Shafts*
	LOX - LH2	RD-0120	Booster - Energia	400,000 SL	Single Shaft and 2 LP
Staged Combustion - Oxidizer Rich	LOX - RP1	RD-170	Booster - Zenit	1,600,000 SL	Single Shaft and 2 LP
	LOX - RP1	RD-120	Upper Stage - Zenit	187,000 Vac	Single Shaft and 2 LP
	NTO - UDMH	RD-253	Booster - Proton	330,000 SL	Single Shaft

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Current and past engine systems span a wide range of cycles, propellants, applications and turbopump configurations. Possible new vehicles such as RLV (Reusable Launch Vehicle), LFBB (Liquid Flyback Booster), SMV (Space Maneuver Vehicle) and commercial boosters and upper stages will expand the range of configurations further. Each presents a unique combinations of shaft sealing requirements for which existing experience is inadequate.

Influence of Rocket Engine Characteristics on Shaft Seal Technology Needs

- **Conclusion -- New propulsion systems for launch vehicles inevitably place new demands on shaft seal systems that are not adequately met with existing seal technology.**

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Slide 14

Seal requirements vary greatly with the the engine application. Future engine needs must be considered in formulating seal component development plans for rocket engine use. Just as important, new engine programs must consider shaft seal needs in their technology development plans.

BANTAM CONTROL SURFACE/TPS SEALS DEVELOPMENT

Juris Verzemnieks and Chuck Newquist
Boeing
Seattle, Washington

BANTAM Control Surface/TPS Seals Development

Objective:

Develop advanced control surface seals and demonstrate using appropriate high temperature test facilities

Approach

Determine seal requirements

Select candidate seal concepts/materials

Perform thermal/structural analyses

Test seal concepts under representative conditions using ARC Arc-jet heating facility

Provide seal designs/databases to vehicle programs for successful implementation and flight

PHANTOM WORKS

BANTAM Control Surface/TPS Seals Development

Outline of Activities

Technical Interchanges & Lessons Learned with:

- X-38 at JSC
- X-37 at Boeing,Seal Beach
- NASA Ames Research Center
- Seal/TPS fabricators

Thermal Analysis of Control Surface Gap

- Use X-38 environment and preliminary design
- CFD Analysis with Permeable Seal

Designed and Fabricated Arc-Jet Test Article Mock-Up

PHANTOM WORKS

BANTAM Control Surface/TPS Seals Development

Lessons Learned/Background

Space Shuttle Experience is Valuable ... but

- •Vehicles like BANTAM, X-38, X-37 are considerably smaller
- •Low temp seals on elevons because Shuttle has sufficient space
- •Smaller Vehicles are Looking at Hot seals for elevons or body flaps

X-37 & X-38 are Designing Bulb type seals

Bulb type seals have considerable experience on Shuttle……however

- Ceramic fiber cloth over Inconel woven spring and insulation -- Nextel 312 (2000F multi use)
- Semi-static applications
- Temps only to 1600 F

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BANTAM Control Surface/TPS Seals Development

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Lessons Learned/Background -- continued

X-33 TPS Seals Use Similar Design as Shuttle

Change is Nextel 440 Cover and stiffer, knitted, Inconel Spring.

Very little data on sliding wear behavior of ceramic fiber covered bulb seals

- Steinetz, et. al. Published data on testing all-ceramic braided rope seals
- Anecdotal evidence that harness satin weaves provide better sliding wear than plain weave -- providing that sliding direction is parallel to face fibers
- Current fabricators may not differentiate between warp and fill faces when wrapping fabric

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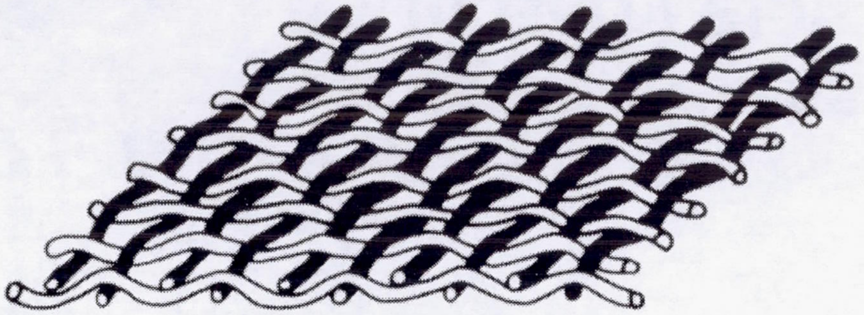
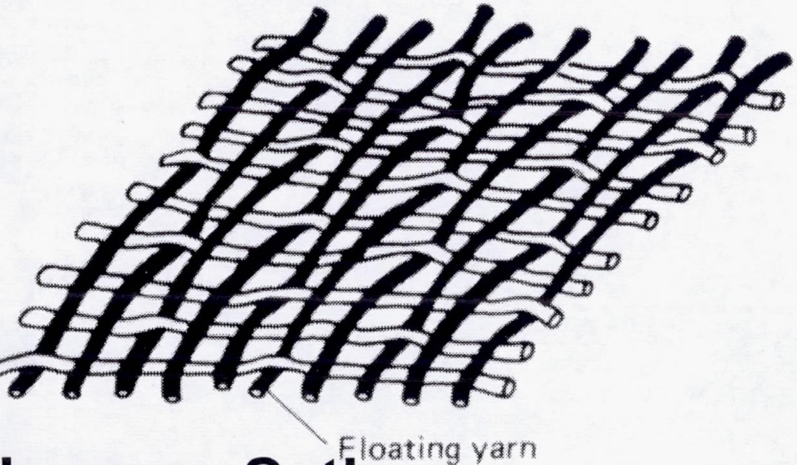
BANTAM Control Surface/TPS Seals Development



Plain Weave



5 Harness Satin

<u>Direction</u> of Sliding Contact Relative to Fabric <u>Orientation</u> is Critical

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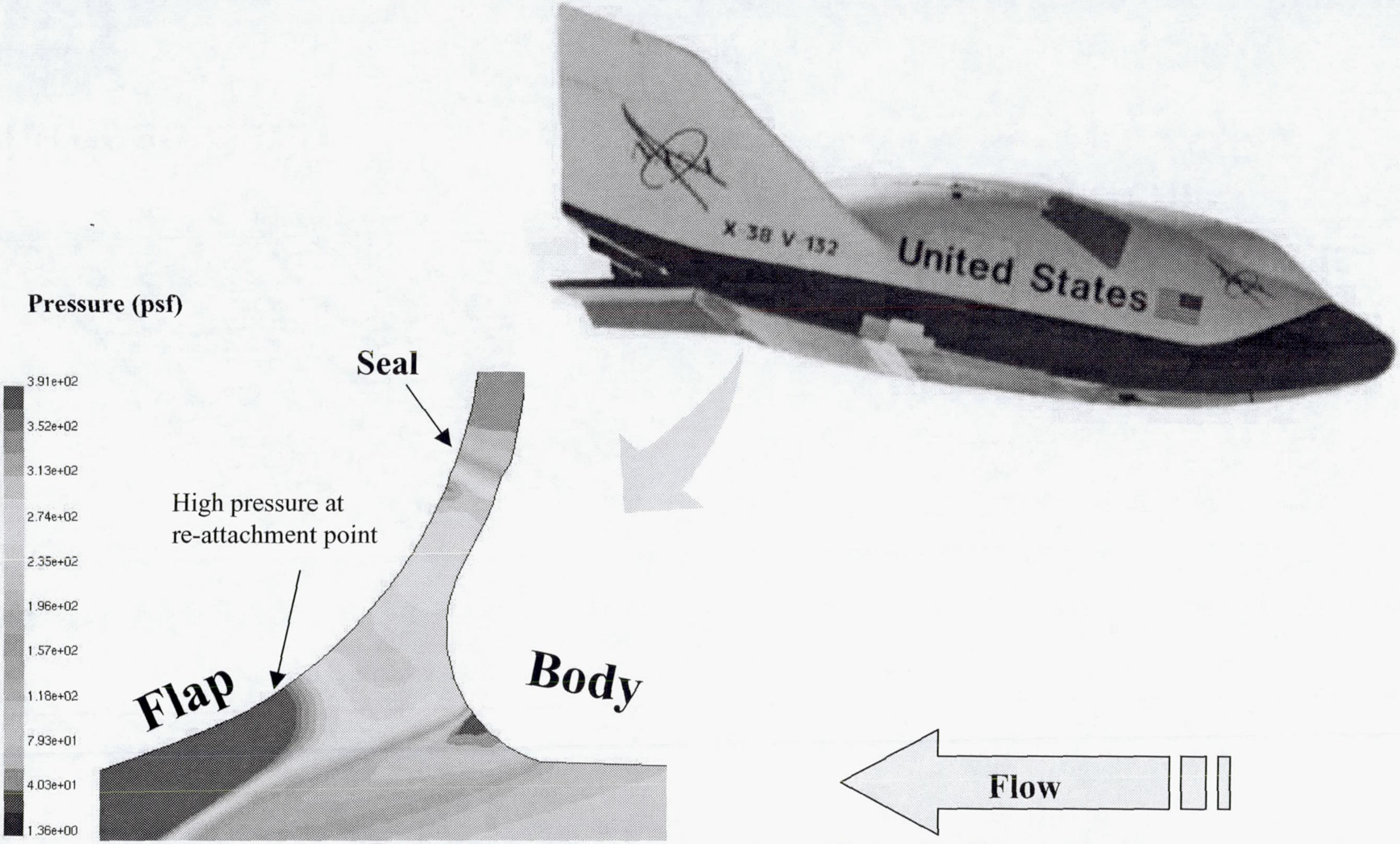
BANTAM Control Surface/TPS Seals Development



Static Pressure Distribution In Body Flap Gap & Seal Area

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BANTAM Control Surface/TPS Seals Development

X-38 Bodyflap Seal Preliminary Aerothermal Analysis

Method

- 2-D Navier-Stokes analysis using commercial CFD code FLUENT
- Limited computational domain for faster turn-around
- Evaluate effect of seal permeability
- Use CFD results at key trajectory points to scale simpler methods for entire trajectory
- Apply predicted environments to structural thermal analysis to determine seal temperatures

Current Assumptions

- Boundary layer growth upstream of domain neglected
- Steady 2-D flow
- Turbulent boundary layer
- 20 degree bodyflap deflection angle
- Radiation equilibrium surface condition (ε=0.8, F = 0.144)
- Rectangular shaped seal (to simplify computational grid)

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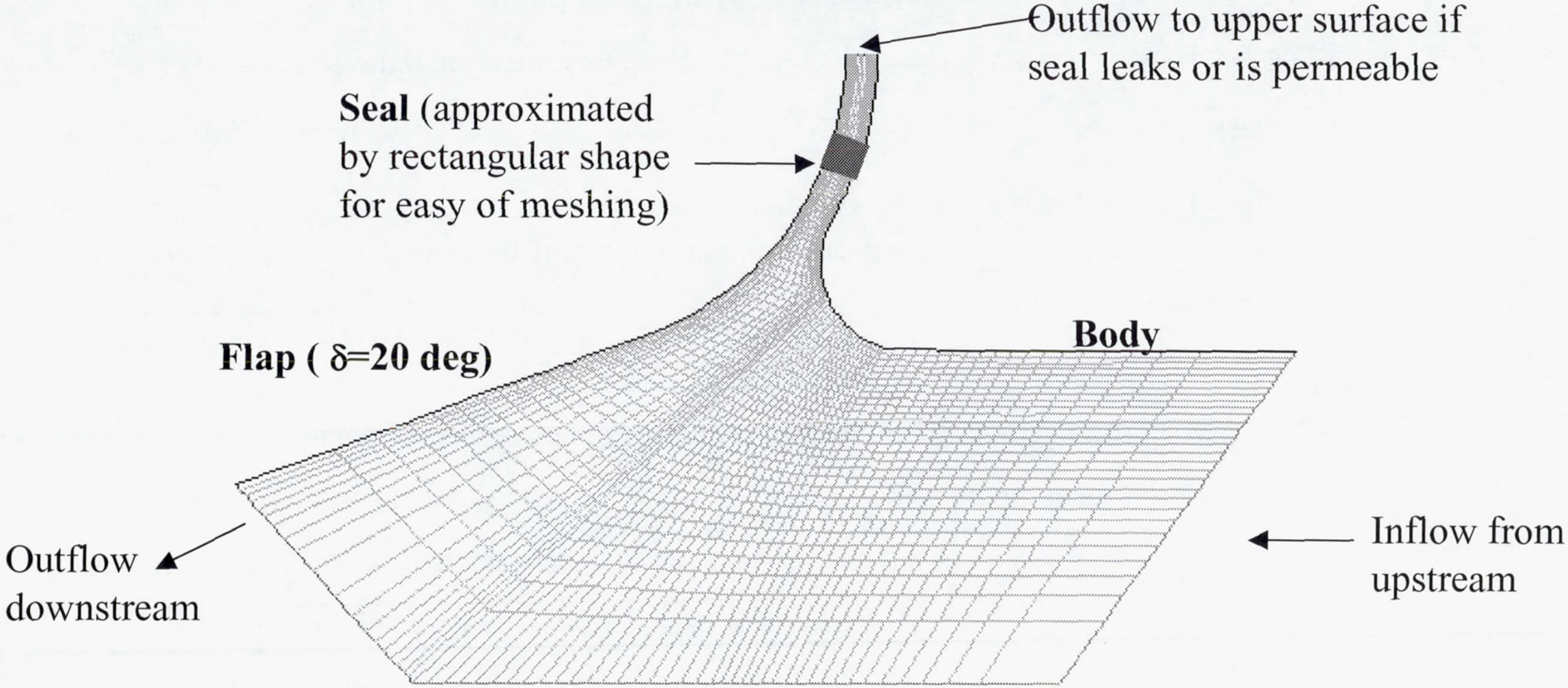
BANTAM Control Surface/TPS Seals Development

X-38 Bodyflap Seal Preliminary Aerothermal Analysis

Computational Grid



Extent of region modeled kept small to decrease preliminary analysis time

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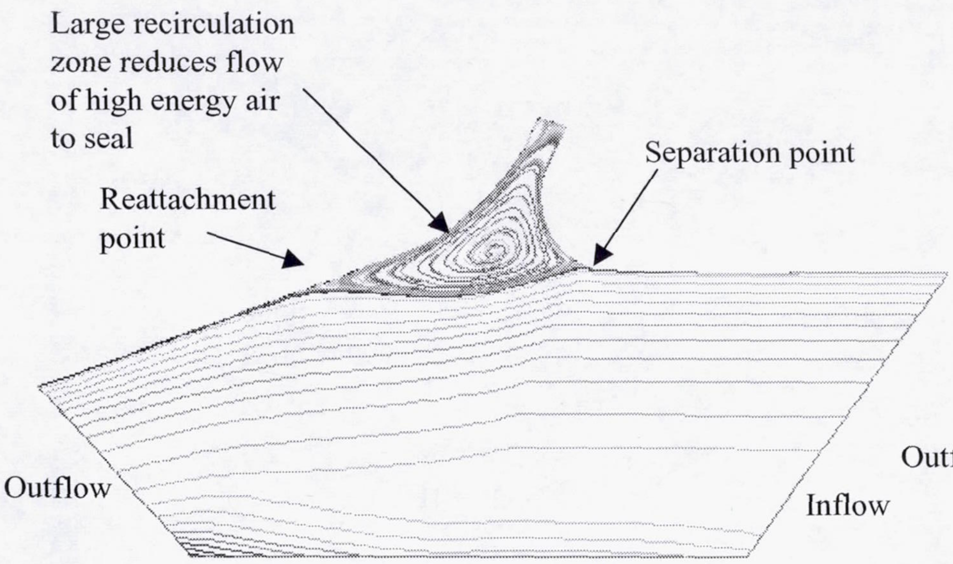
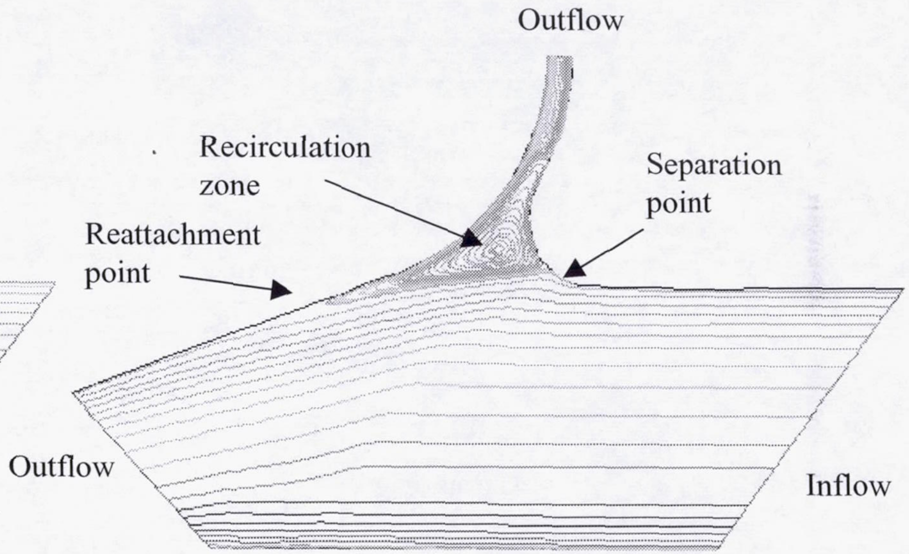
BANTAM Control Surface/TPS Seals Development

X-38 Bodyflap Seal Preliminary Aerothermal Analysis

Impermeable Seal



Permeable Seal (k = 1.0e-7)



Flow Pathlines

A permeable seal does not significantly influence flow field structure

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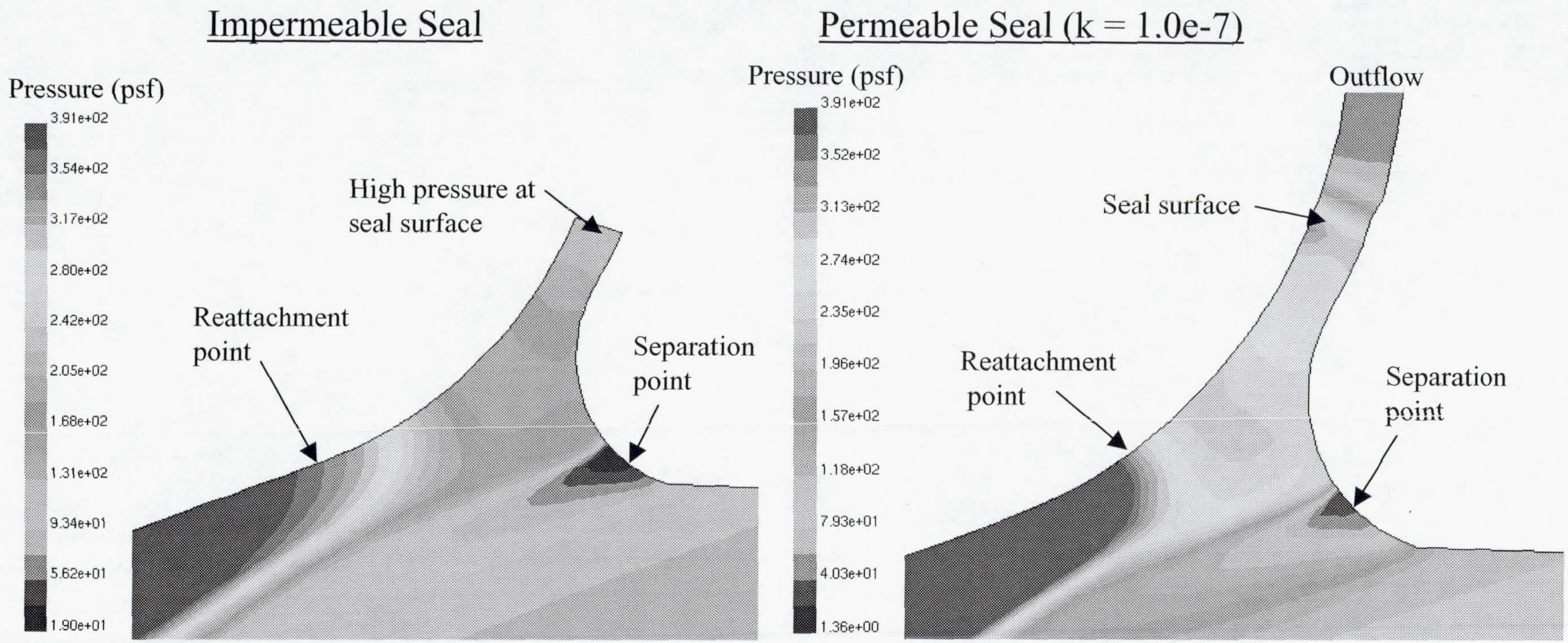
BANTAM Control Surface/TPS Seals Development

X-38 Bodyflap Seal Preliminary Aerothermal Analysis



Static Pressure Distribution

Flow through permeable seal does not significantly affect pressure at the seal surface

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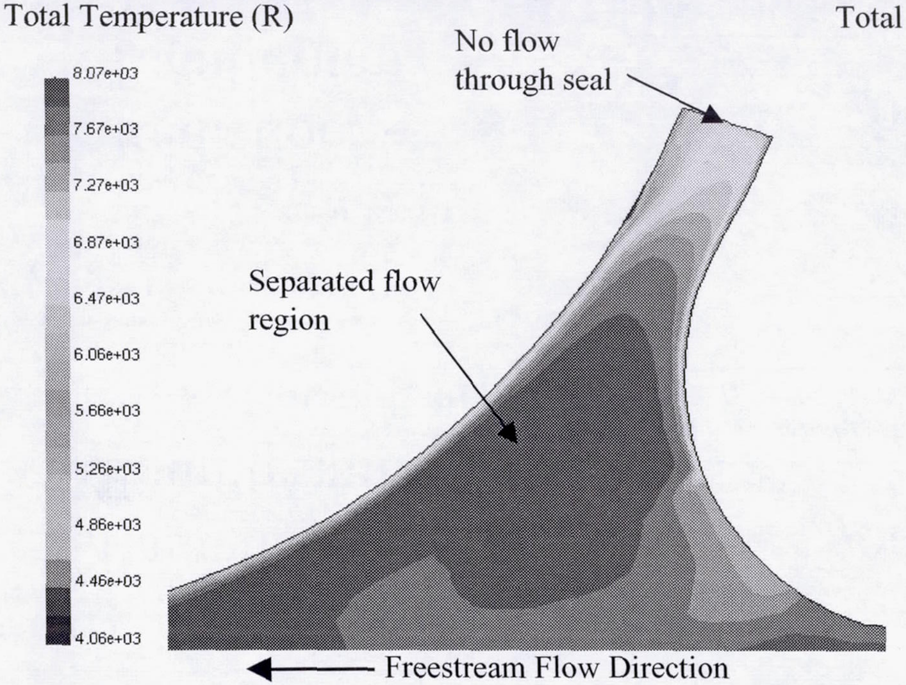
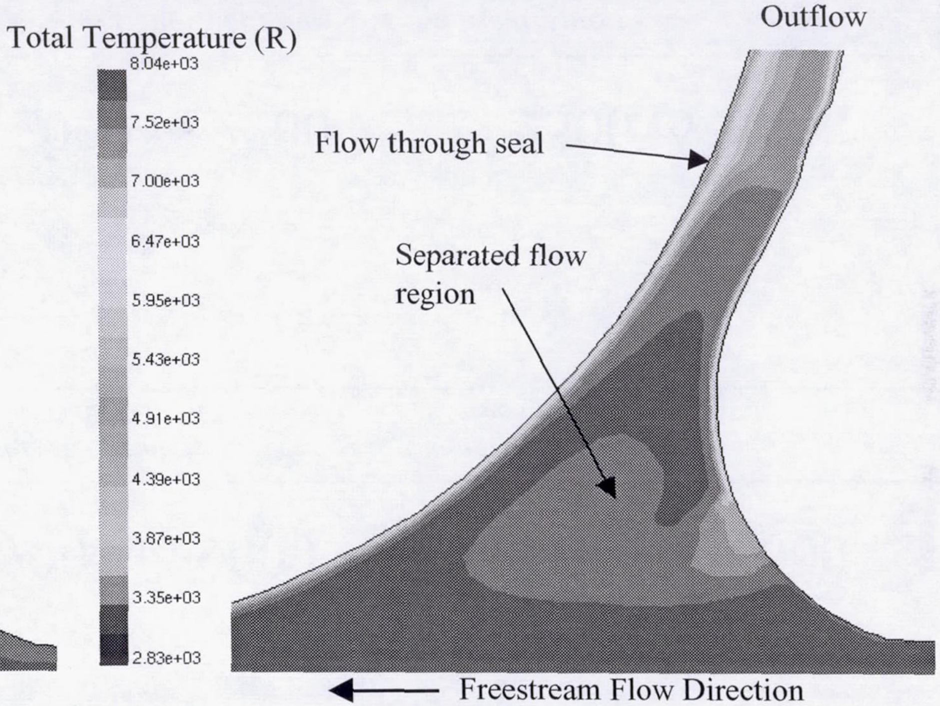
BANTAM Control Surface/TPS Seals Development

X-38 Bodyflap Seal Preliminary Aerothermal Analysis

Impermeable Seal



Permeable Seal (k = 1.0e-7)



Total Temperature Distribution

Permeable seal allows hotter flow to seal surface

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BANTAM Control Surface/TPS Seals Development

Seal Surface Condition (20° flap δ)	**Impermeable**	**Permeable**
Radiation Equilibrium Heat Flux (Btu/sq ft-hr)	7000 to 9000	15000 to 30000
Radiation Equilibrium Temperatures (°F)	2000 to 2200	2500 to 3000

Seal permeablility significantly increases seal heating

Note: Heat flux from the flow into the seal is defined as a negative value in FLUENT .

High seal permeablility significantly increases seal temperatures

Note: These radiation equilibrium temperatures are only a rough estimate of actual material temperatures. A transient structural thermal analysis is required to accurately predict seal temperatures.

NASA

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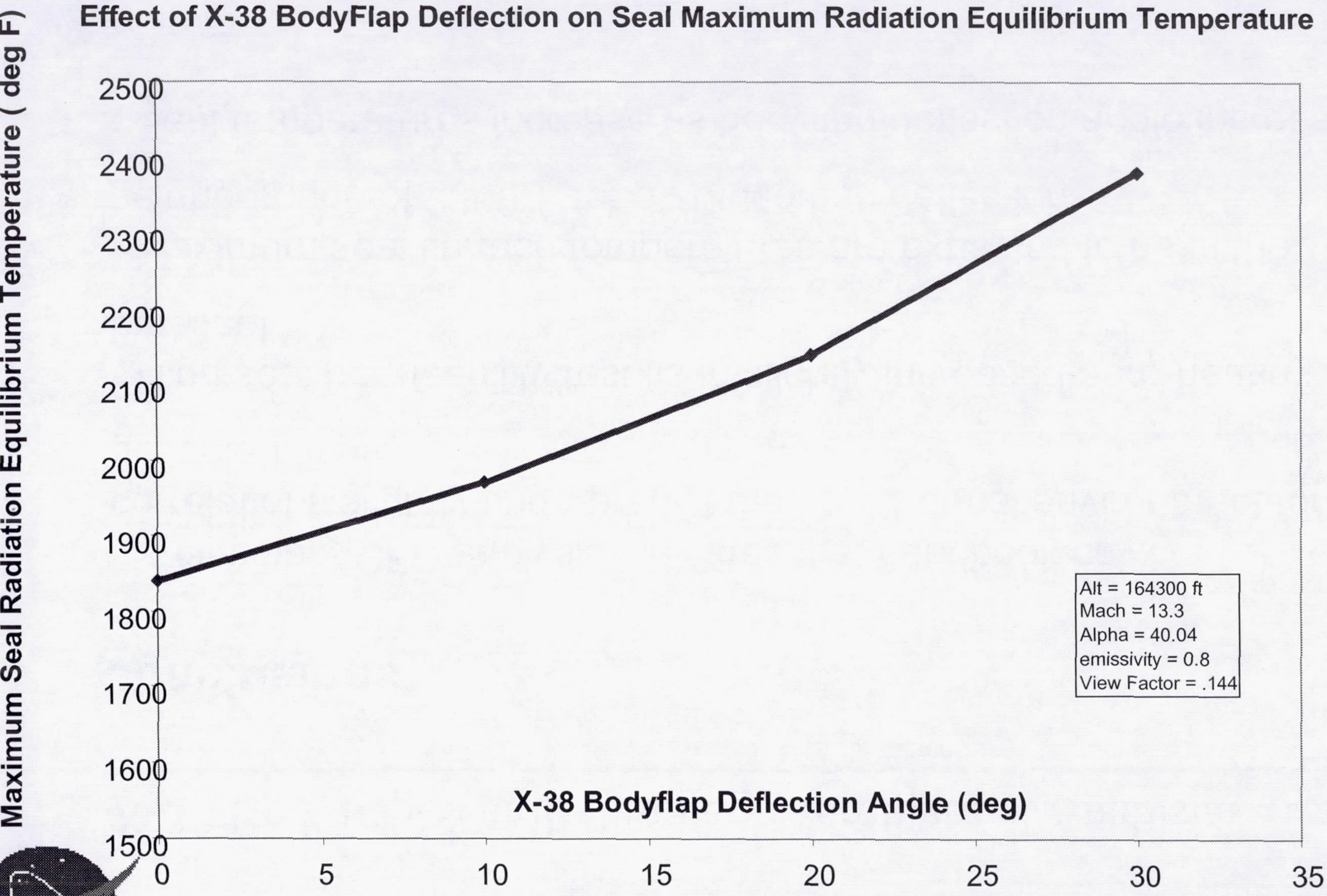
BANTAM Control Surface/TPS Seals Development



BANTAM Control Surface/TPS Seals Development

X-38 Bodyflap Seal Preliminary Aerothermal Analysis

Conclusions

- Preliminary CFD analysis indicates that handbook cavity correlations slightly underpredict the aerothermal environment for deflected flaps.
- High seal permeability results in slightly increased aero-heating to the seal.
- Maximum seal surface temperatures are expected to be in the neighborhood of 2300°F for a 20 deg flap deflection.
- Seal temperatures increase as bodyflap deflection angle increases

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BANTAM Control Surface/TPS Seals Development

Arc-Jet test Fixture for Seals

Features of test article will include:

- Control surface hinge-line seal cavity with replaceable cartridge to quickly and easily change-out candidate seals and seal materials
- Actuated trailing flap to deflect the control surface and assess effects of potential flow ingestion into the control surface hinge-line seal cavity
- Cavity will be well instrumented with probes to measure upstream and downstream pressures and temperatures.
- Test results will be used to validate control surface seal design (ref. Task 6) and aero-thermal analyses (ref. Task 3.)

We Have completed a Mock-Up Article and Evaluated Design in AMES Arc-Jet Facility (PTF)

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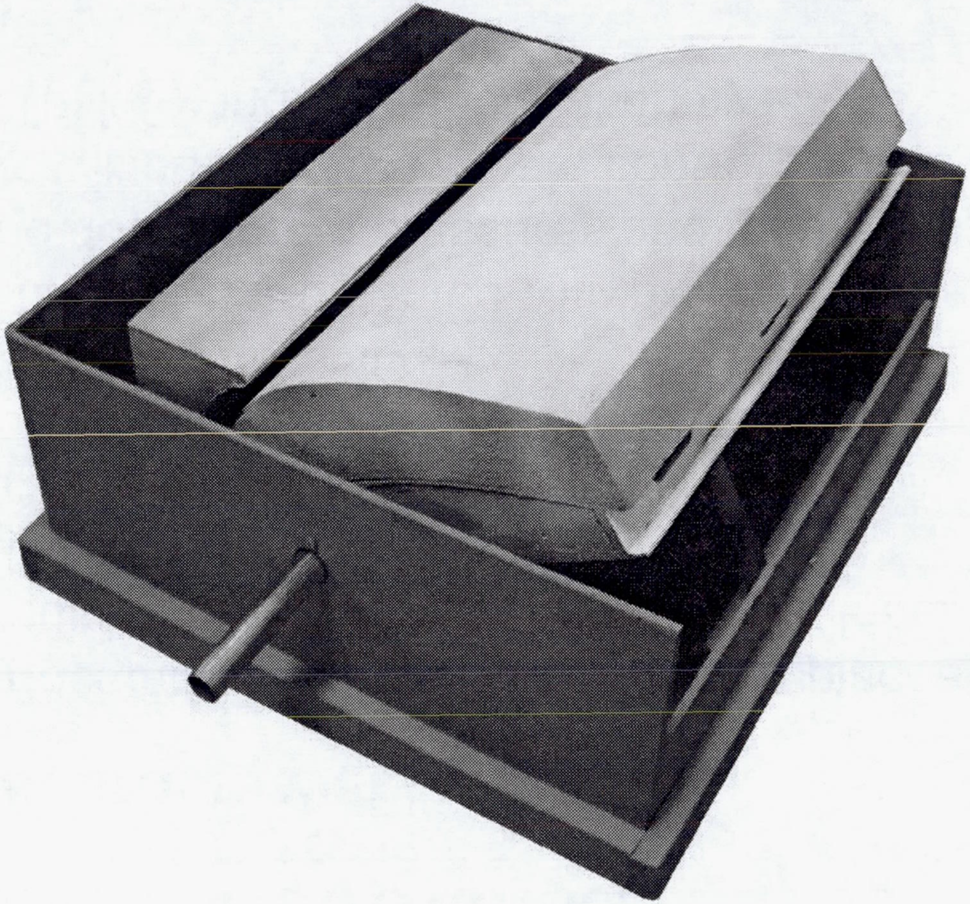
PHANTOM WORKS

BANTAM Control Surface/TPS Seals Development

Mock-Up for Arc-Jet test Fixture for Seals



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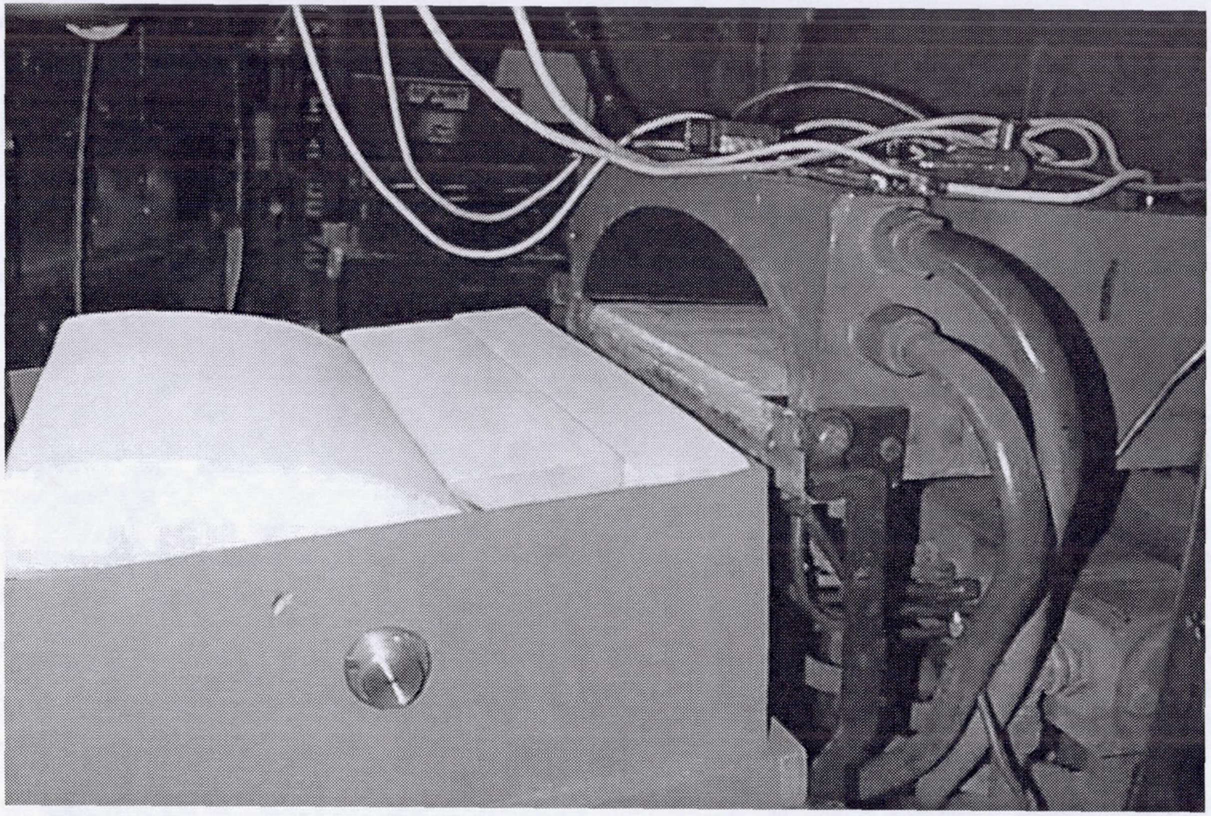
BANTAM Control Surface/TPS Seals Development



Test Article Mock-Up In Ames PTF

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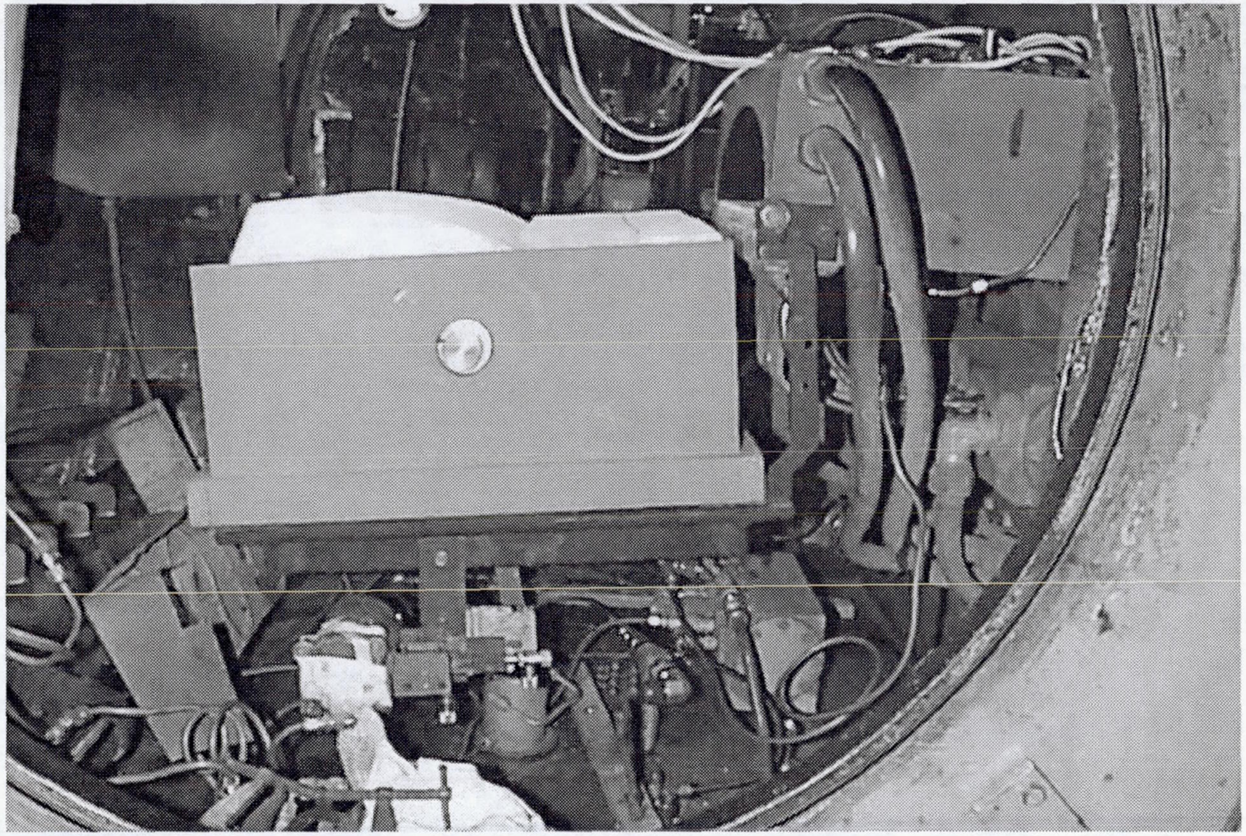
BANTAM Control Surface/TPS Seals Development



Test Article Mock-Up In Ames PTF

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BANTAM Control Surface/TPS Seals Development

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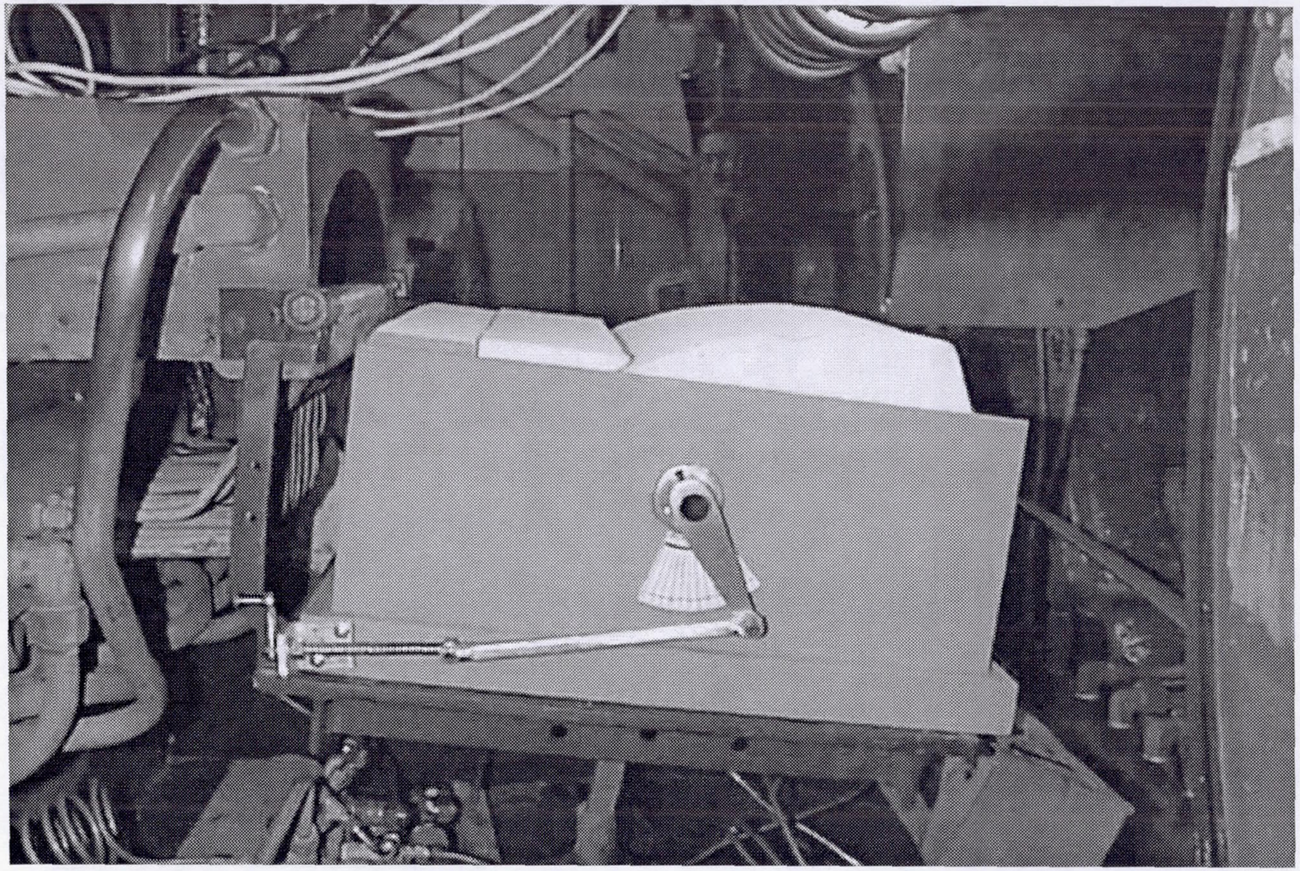

Test Article Mock-Up In Ames PTF

BANTAM Control Surface/TPS Seals Development

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PLANNED CONTINUING ACTIVITIES

Fabricate the Test Article

Design/Fabricate Seals and TPS Components

Complete Thermal/Structural Analysis

Perform Arc-Jet Testing of Seal Designs

X-38 TPS SEAL STATUS

Donald M. Curry
National Aeronautics and Space Administration
Johnson Space Center
Houston, Texas

X -38 TPS Seal Status

Donald M. Curry
NASA Johnson Space Center

1999 NASA Seal/Secondary Air System Workshop
NASA Glenn Research Center
October 28-29, 1999

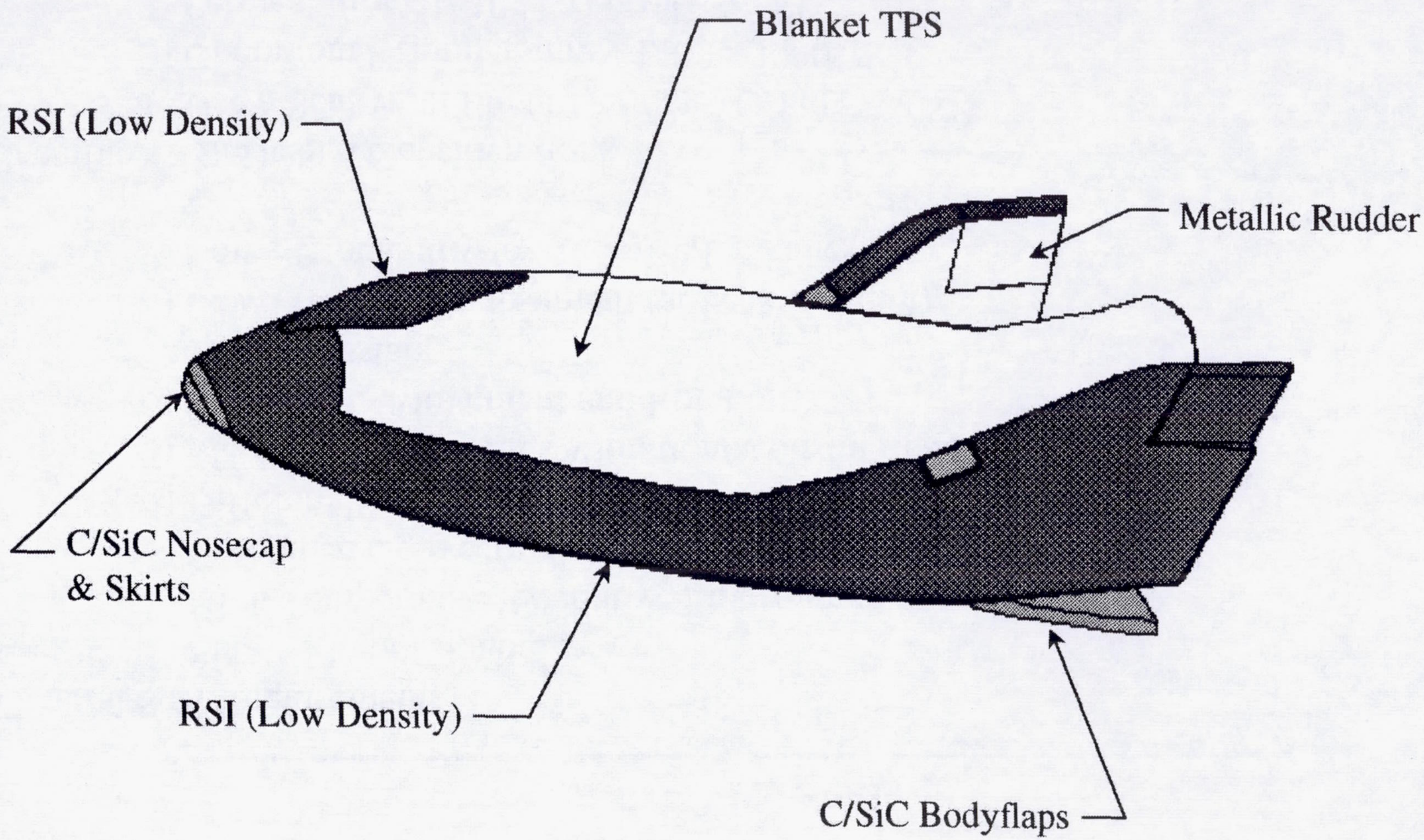
X38 - Crew Return Vehicle

- **An element of the International Space Station (ISS)**

- **Three Scenarios**
  - ISS catastrophe
  - Emergency medical evacuation
  - Period of Space Shuttle unavailability

- **X-38 Program Purpose:**
  - To greatly reduce the costs and schedule for the development of Crew Return Vehicles (CRV's) and Crew Transfer Vehicles (CTV's) through the use of the rapid development methodology associated with an X-project
    - **Ground Testing**
    - **Atmospheric Testing**
    - **Space Flight Testing**

X-38 TPS Configuration



X38 - TPS Seals

General Seal Requirements

1) Single Flight Capability
2) High Temperature, Oxidative Environment
3) Combined Convective and Radiation Heating
4) Different Thermal Expansion of Seal Parts
5) Mechanical Load Plus Vibration/acoustic Loads
6) Component Movement and Rotation
7) Wear Resistant
8) Low Pressure Environment (at Peak Heating)
9) Low Permeability to Minimize Leakage

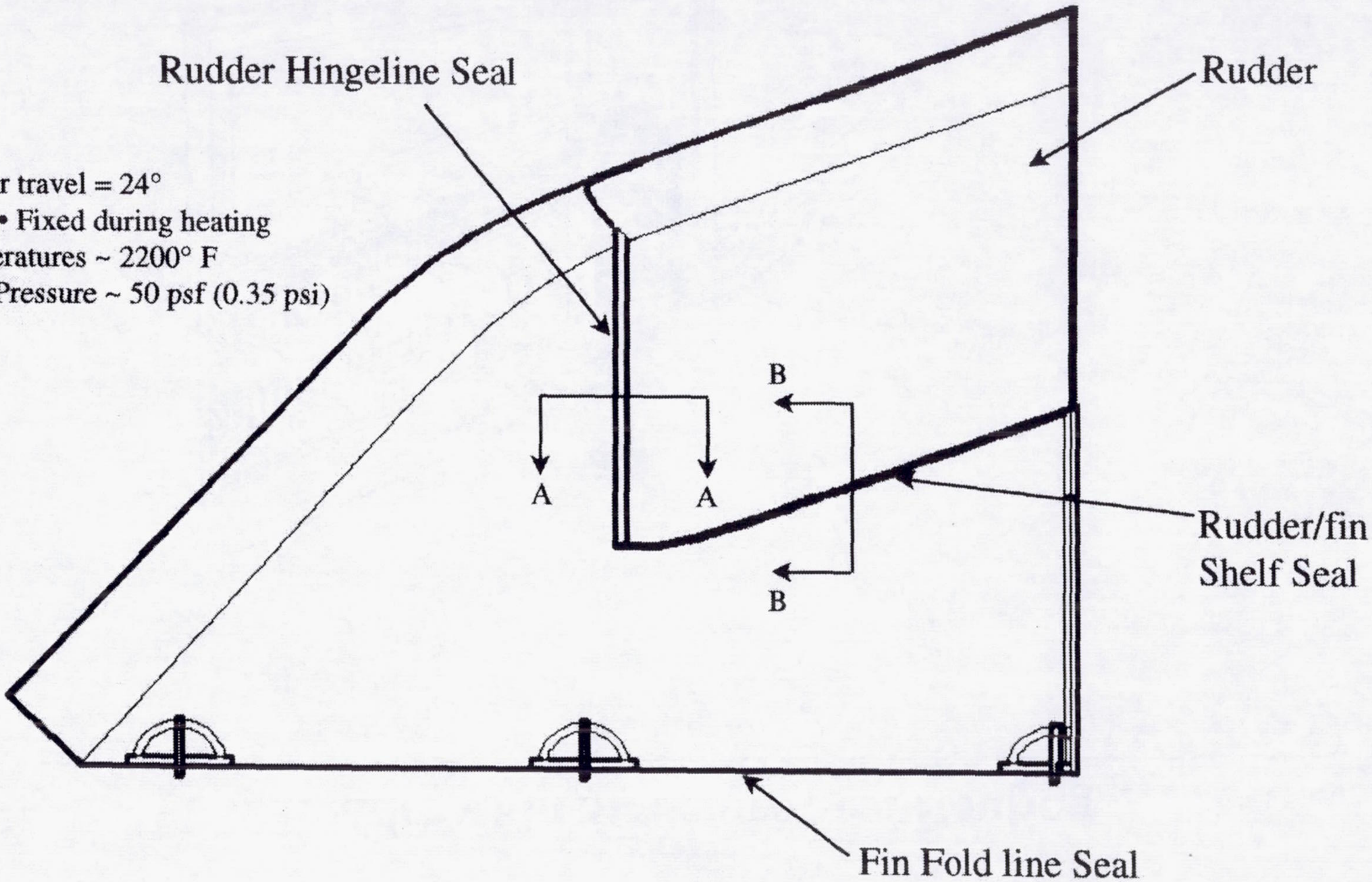
Specific X -38 Design Considerations

1) Use a Seal With Flight Heritage (Orbiter)
2) Operational Temperature - 1500 - 3000°F
3) Permeability - $1x10^{-10}$ - $1x10^{-11}$ Sq. M
4) Coefficient of Friction - 1.09 - 1.17
5) Installation Force Limit of 3 LB/in (Installed With 20-30% Seal Deflection)
6) Differential Pressures of 350 - 450 PSF During Peak Heating

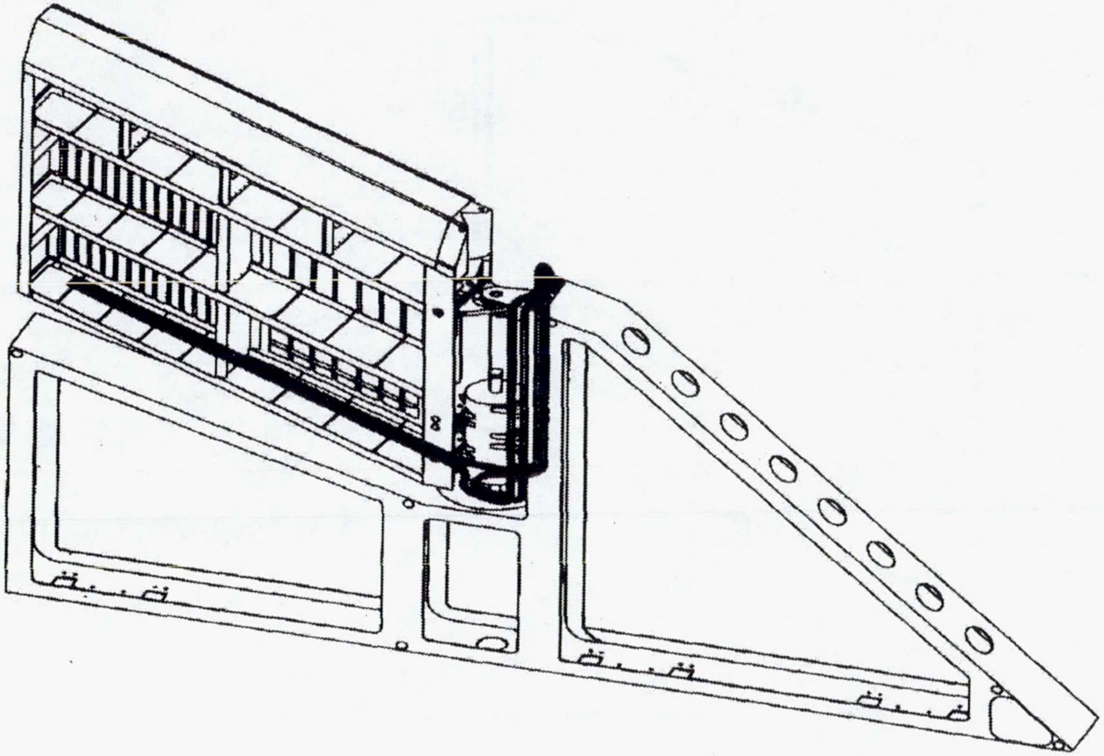
Fin & Rudder Seals

Rudder travel = 24°
- Fixed during heating

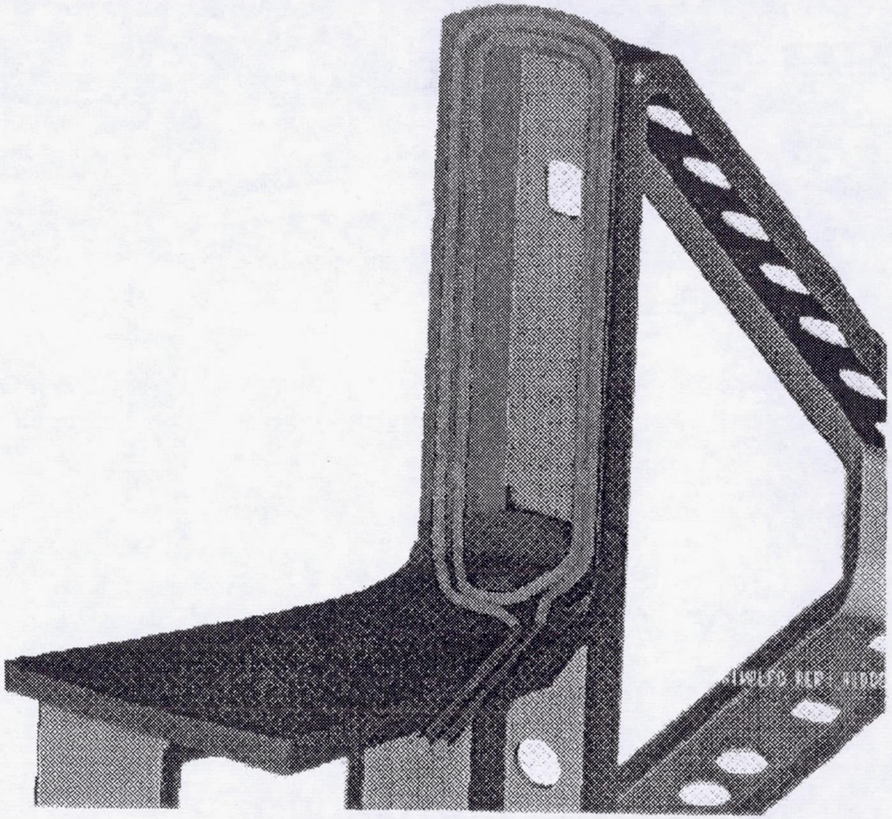
Temperatures ~ 2200° F
Delta Pressure ~ 50 psf (0.35 psi)



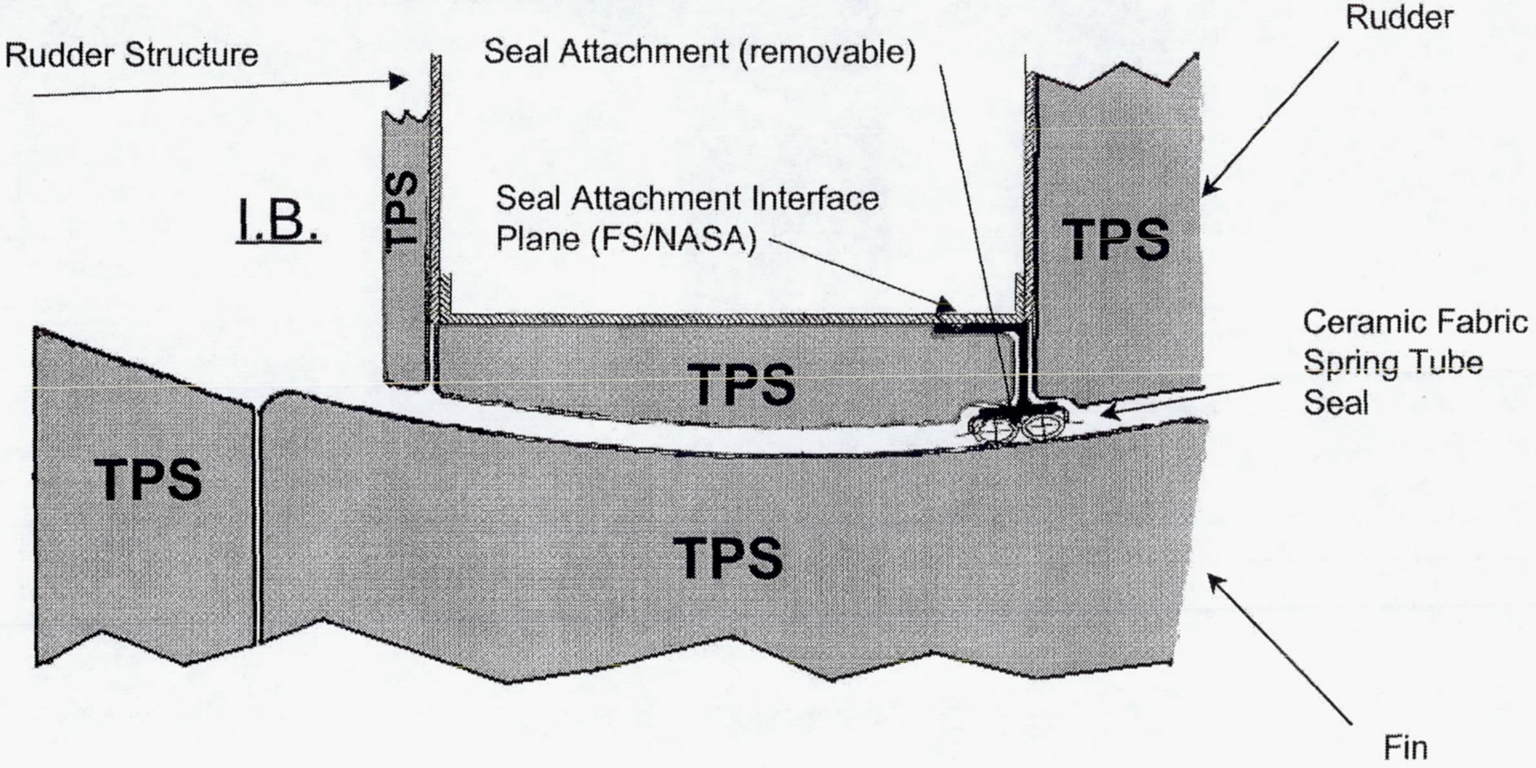
Rudder - Fin Structure Seal Routing



Fin/Rudder Seal

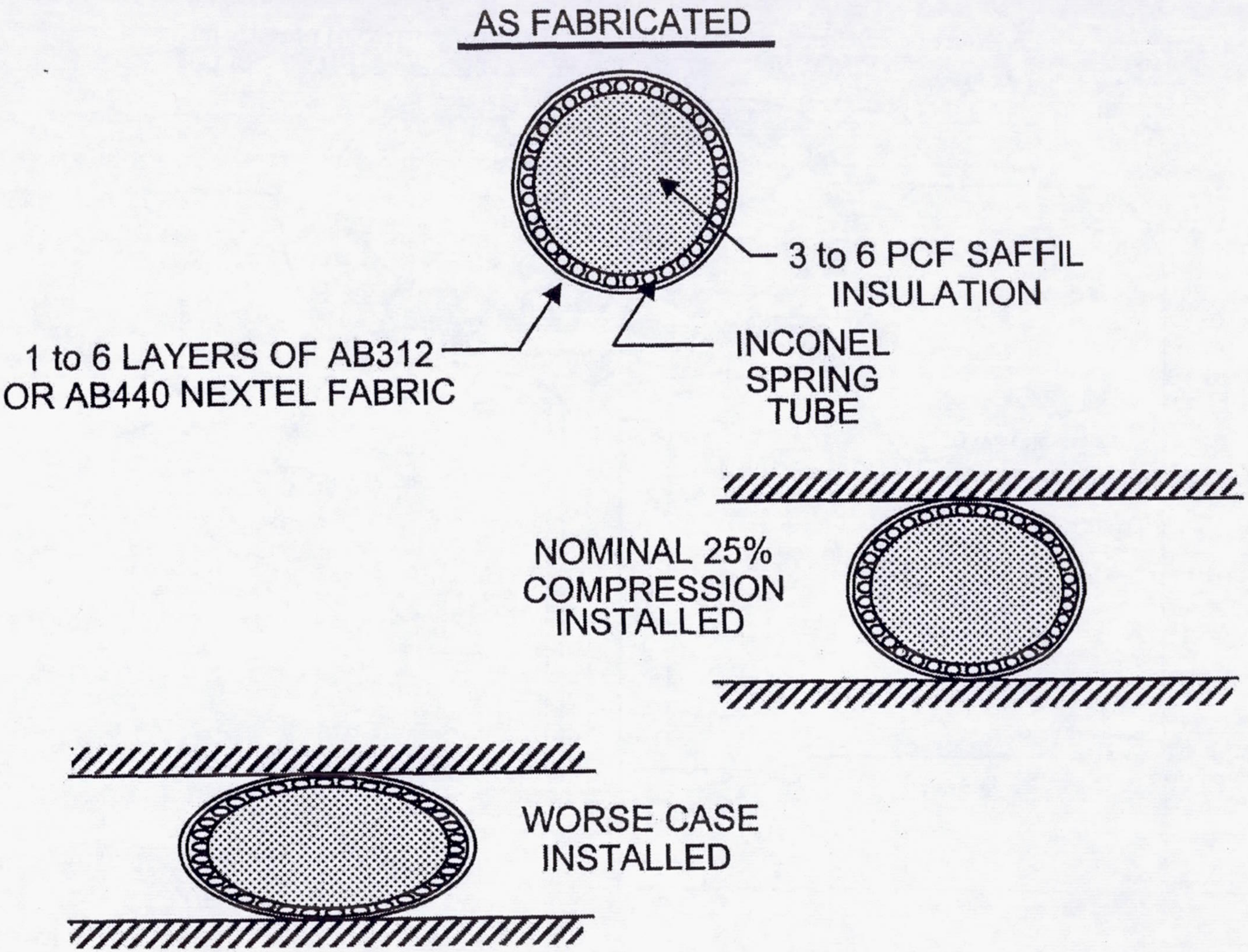


Rudder/Fin Shelf Seal



Section B-B

X-38 TYPICAL SPRING TUBE SEAL



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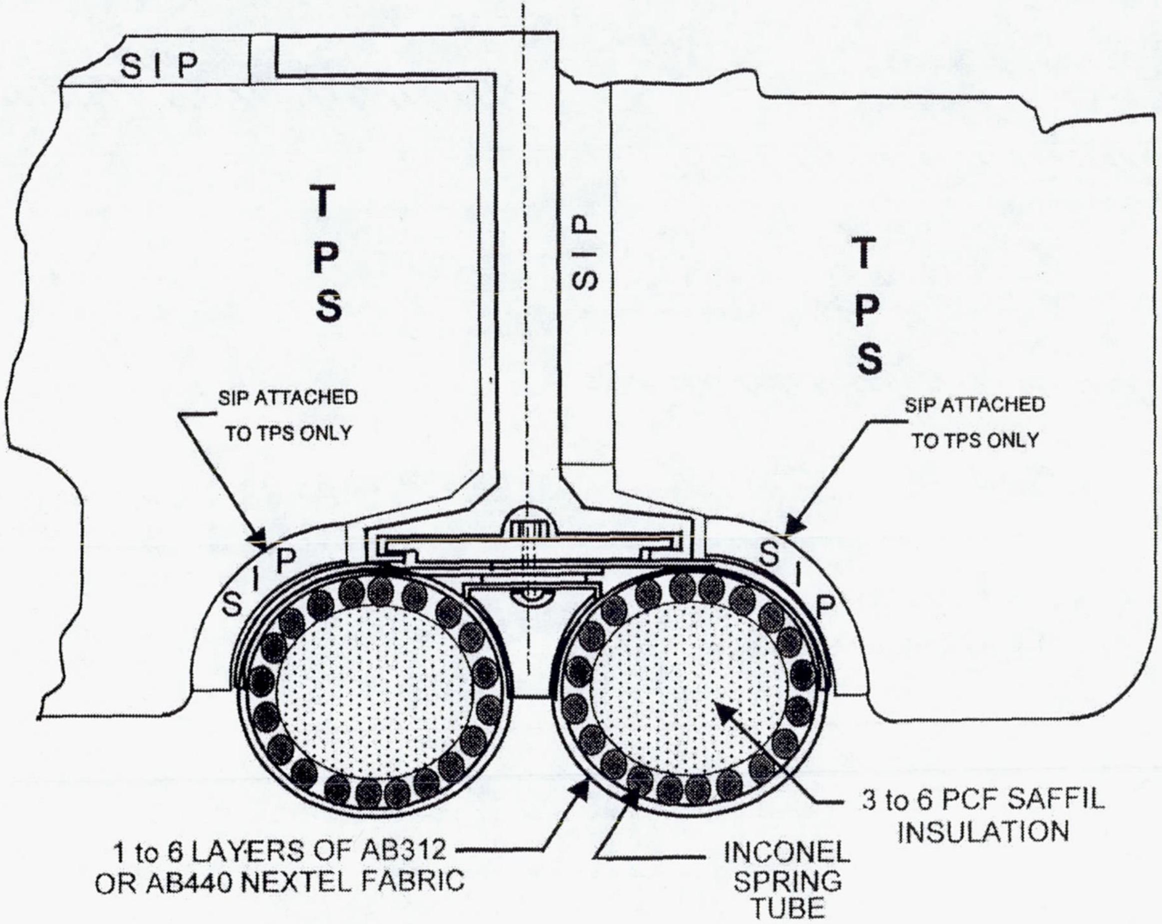
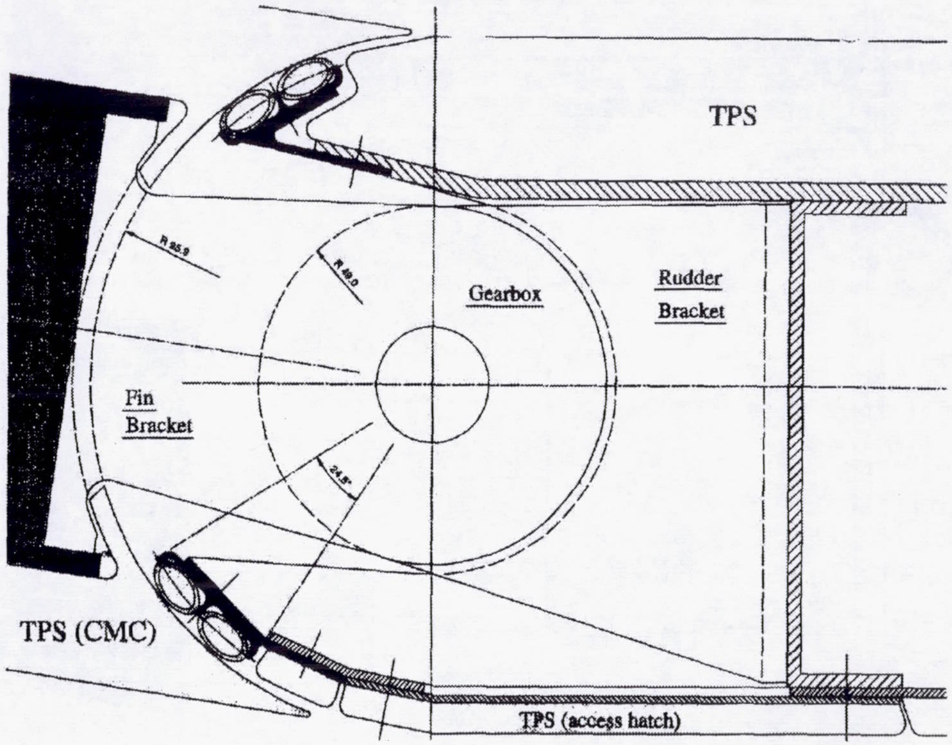

SIP
T P S
SIP
T P S
SIP ATTACHED TO TPS ONLY
SIP ATTACHED TO TPS ONLY
SIP
SIP
3 to 6 PCF SAFFIL INSULATION
1 to 6 LAYERS OF AB312 OR AB440 NEXTEL FABRIC
INCONEL SPRING TUBE

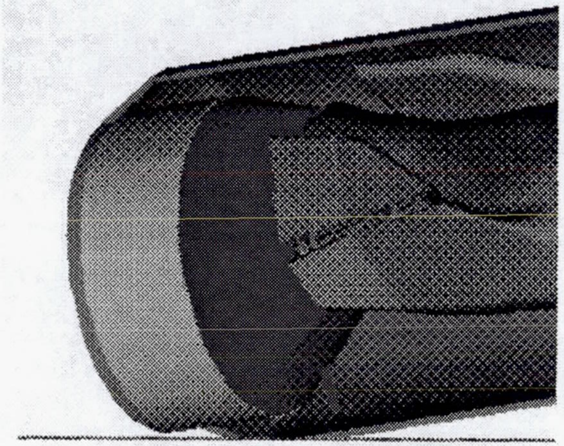
10/22/99

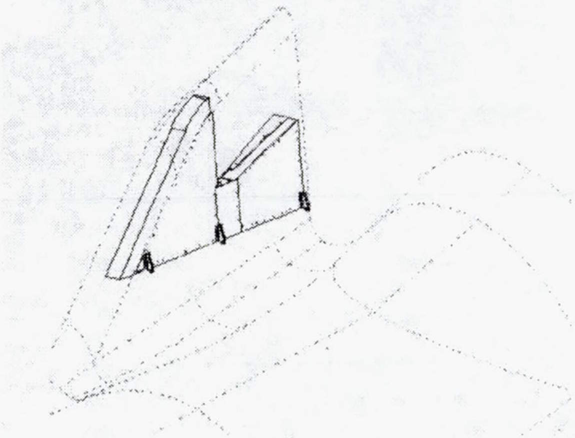
Rudder Hingeline Seal

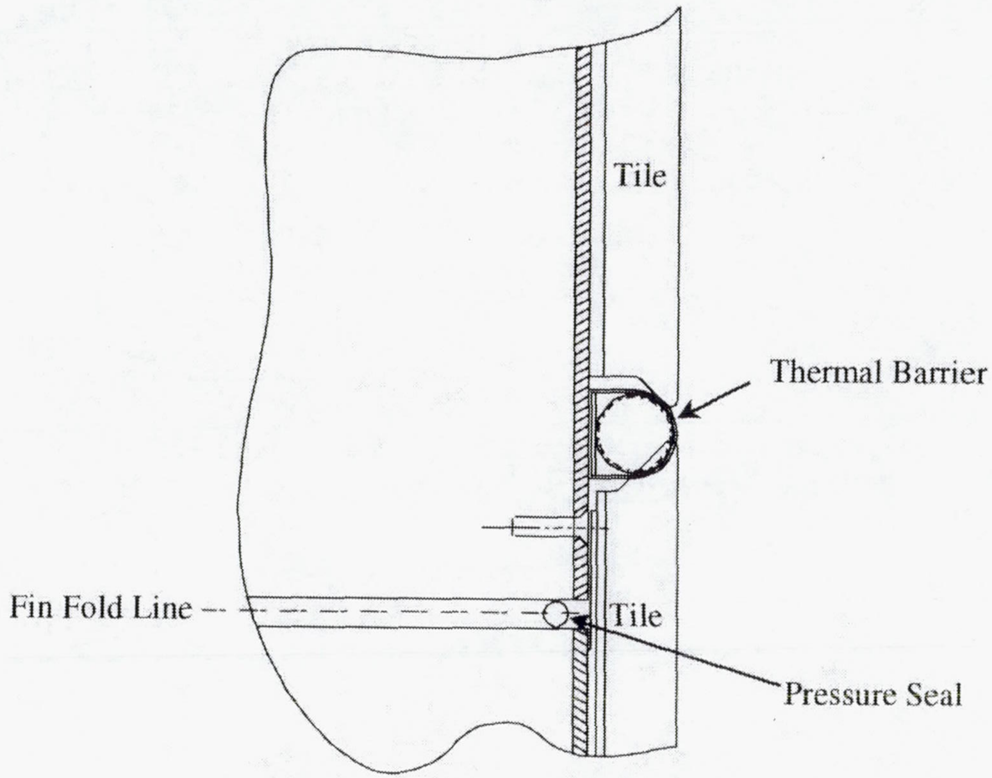


Section A-A

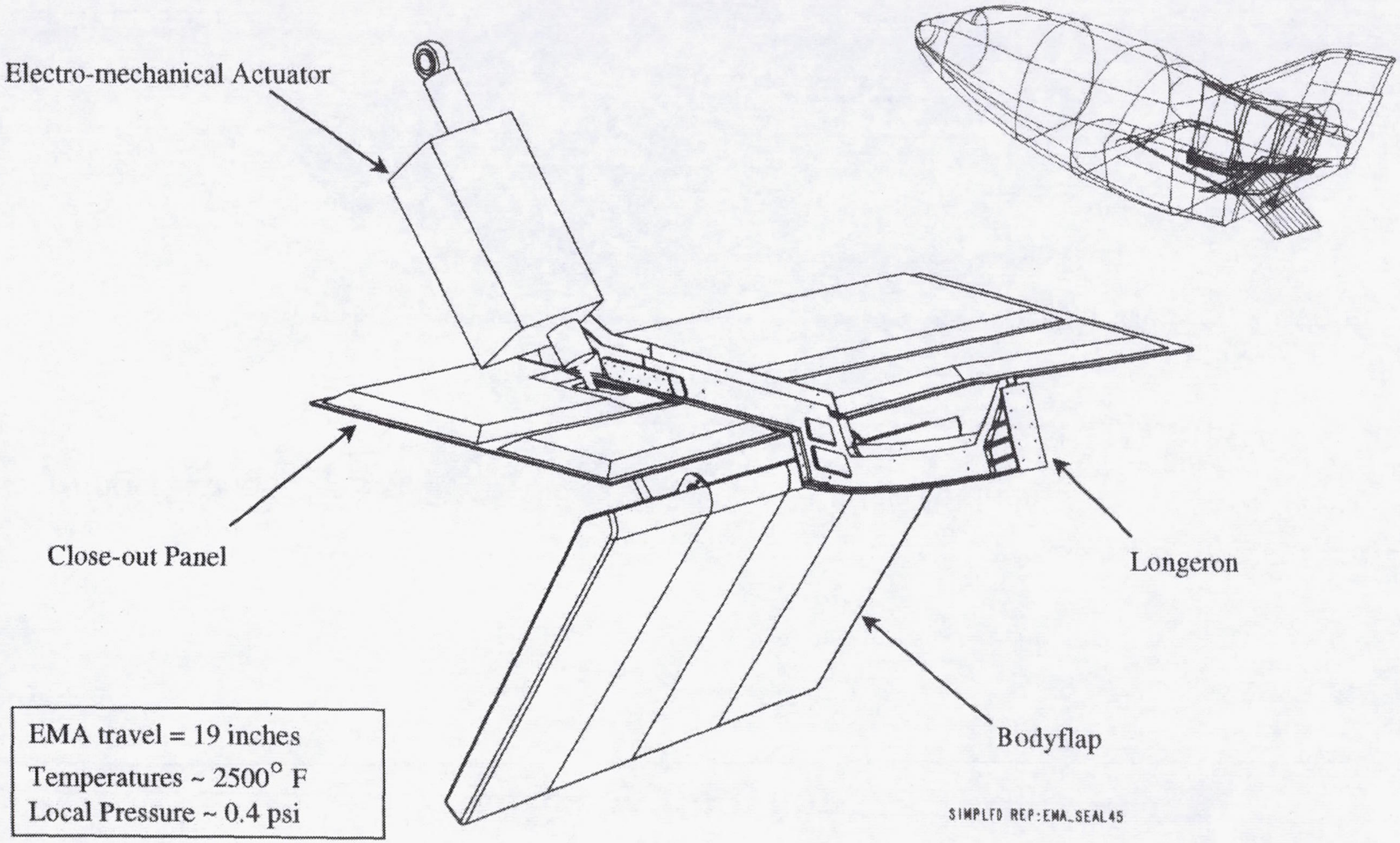
Folding Fin







Bodyflap Configuration

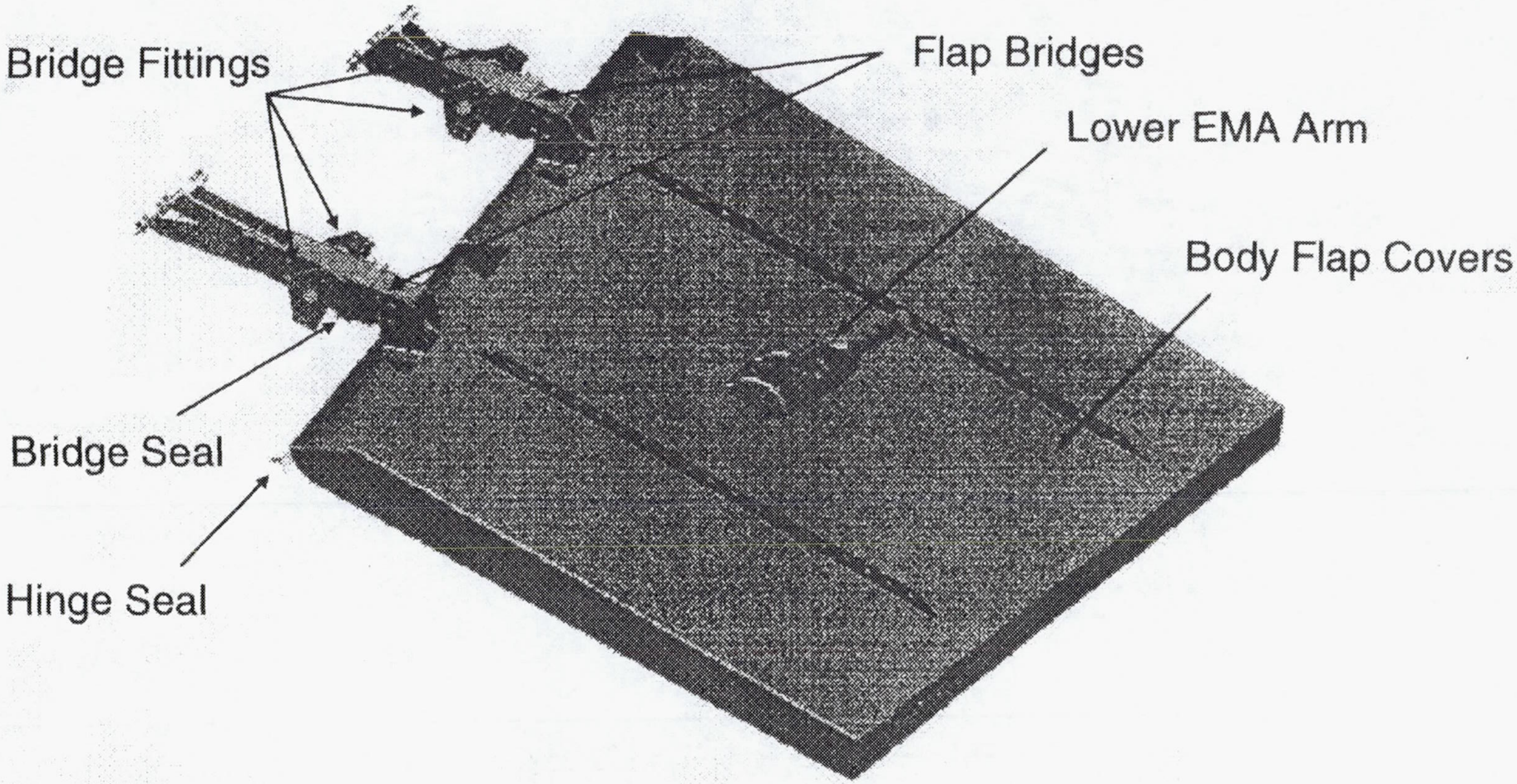


EMA travel = 19 inches

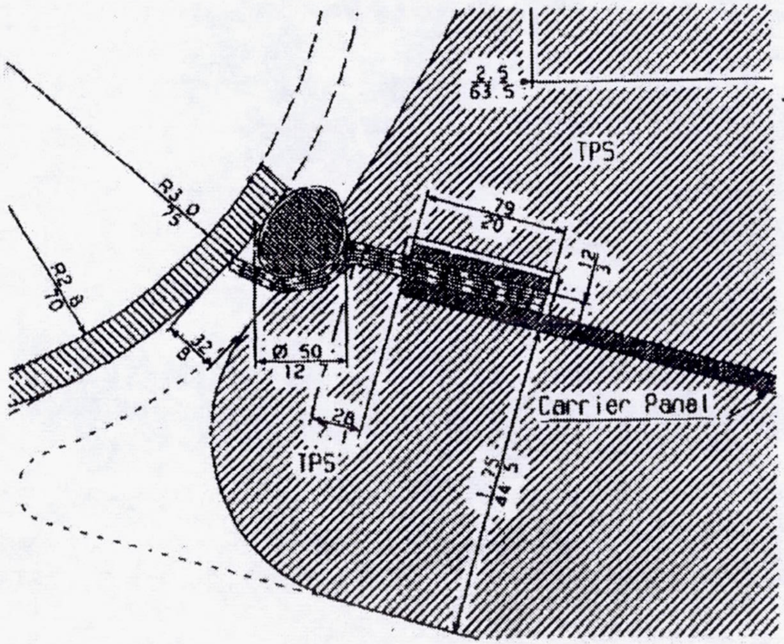
Temperatures ~ 2500° F

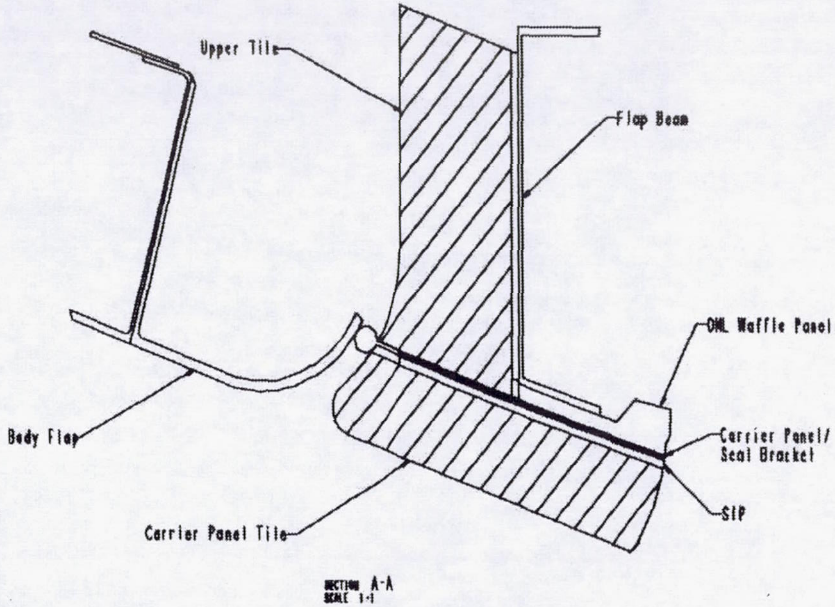
Local Pressure ~ 0.4 psi

X - 38 Bodyflap



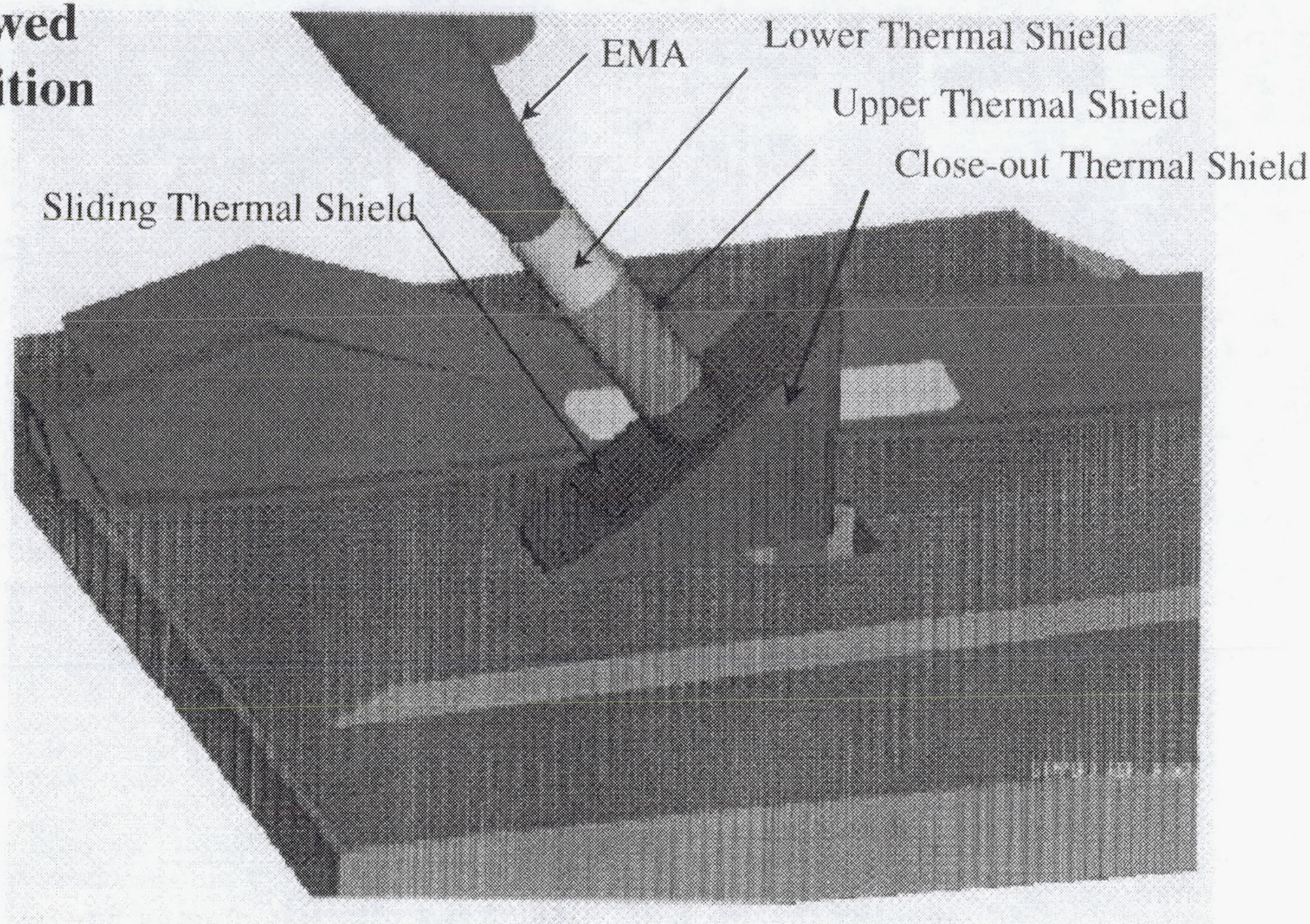
Body Flap Hinge Line Seal



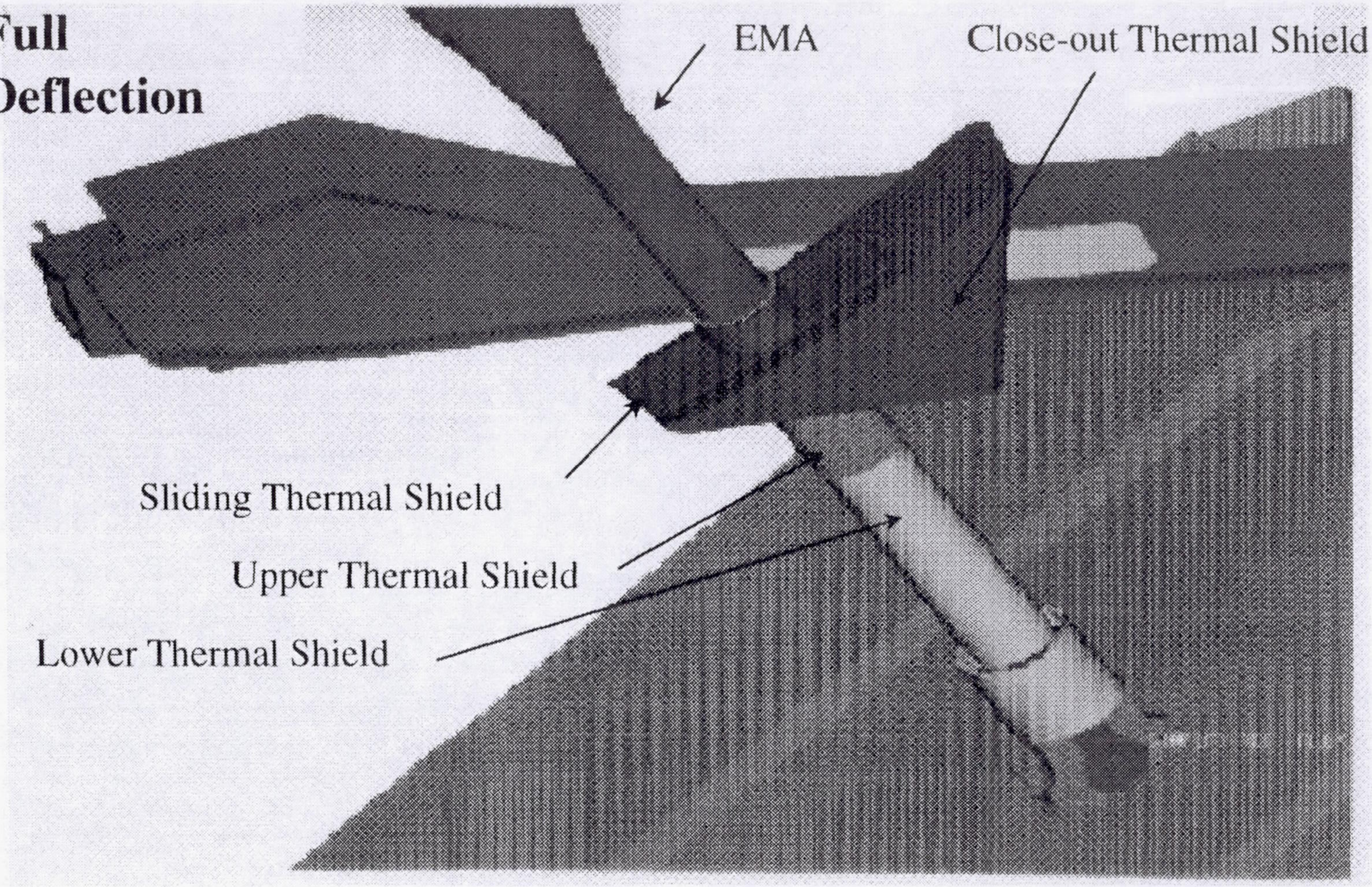


Bodyflap - Undeflected

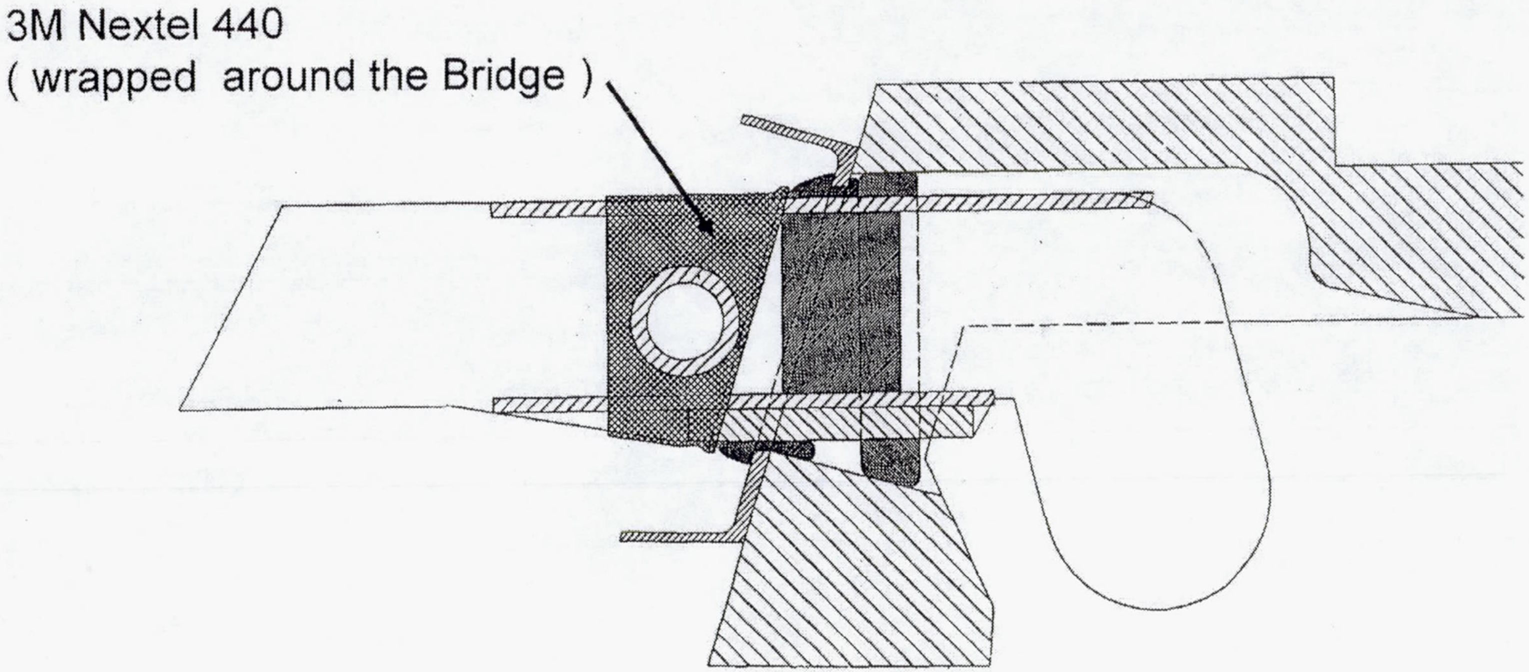
Stowed Position



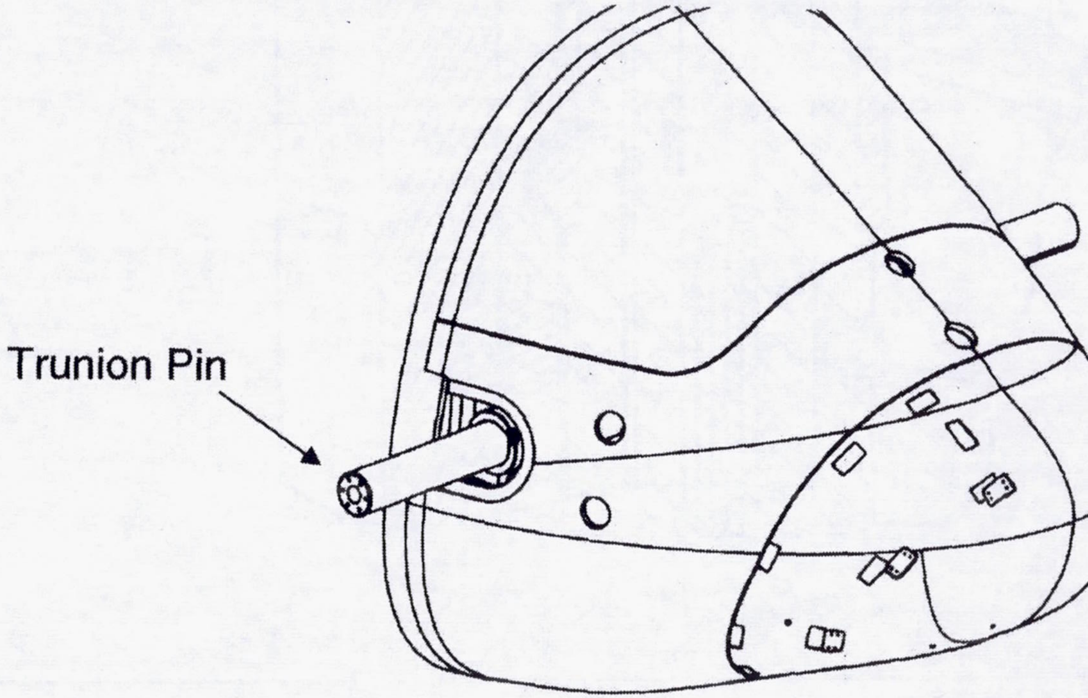
Body Flap - Full Deflection



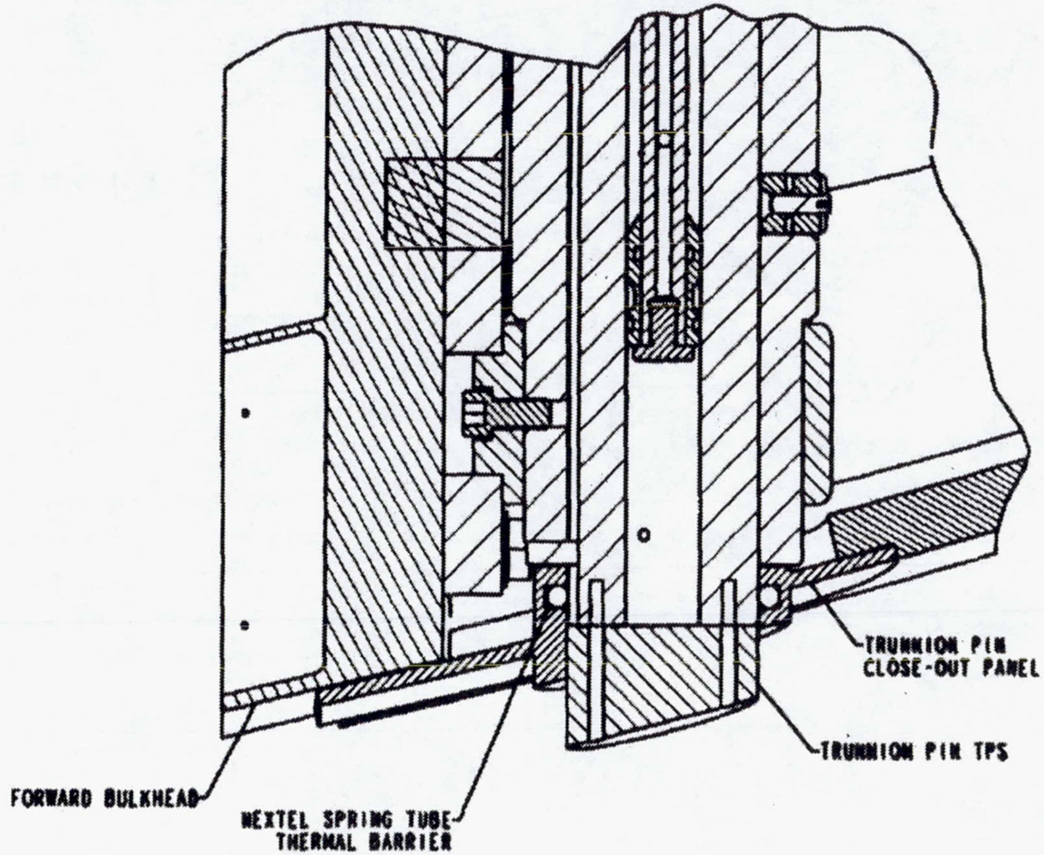
Body Flap Bridge Beam Seal



Forward Trunion Pin



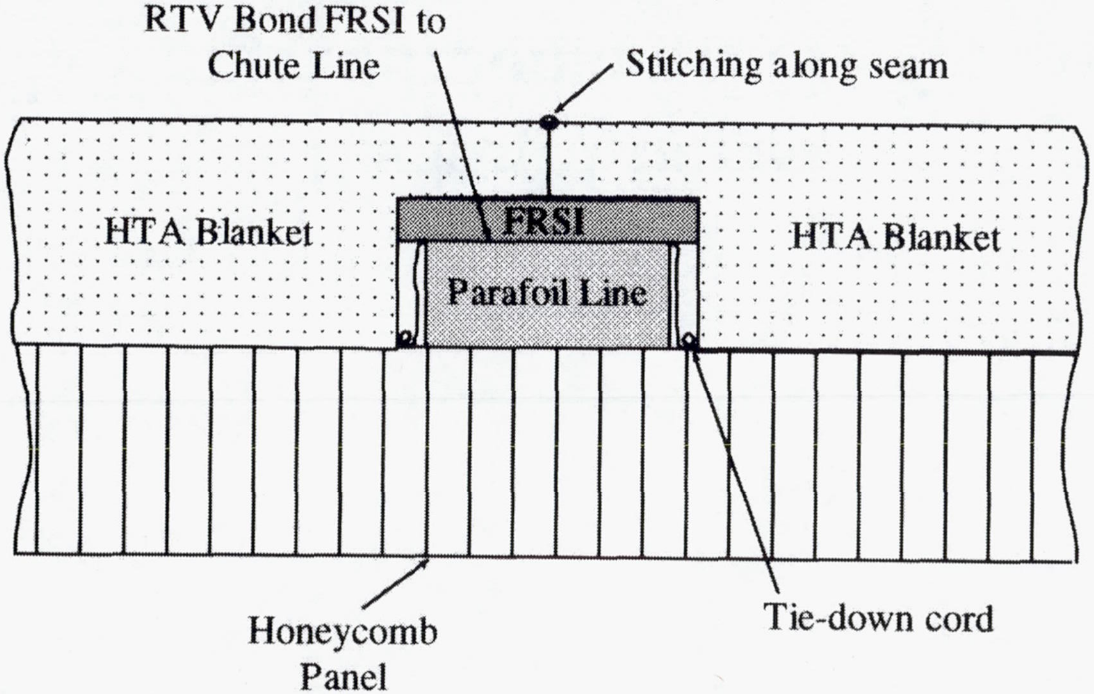
X-38 Forward Trunion Pin Retracted Showing Seal



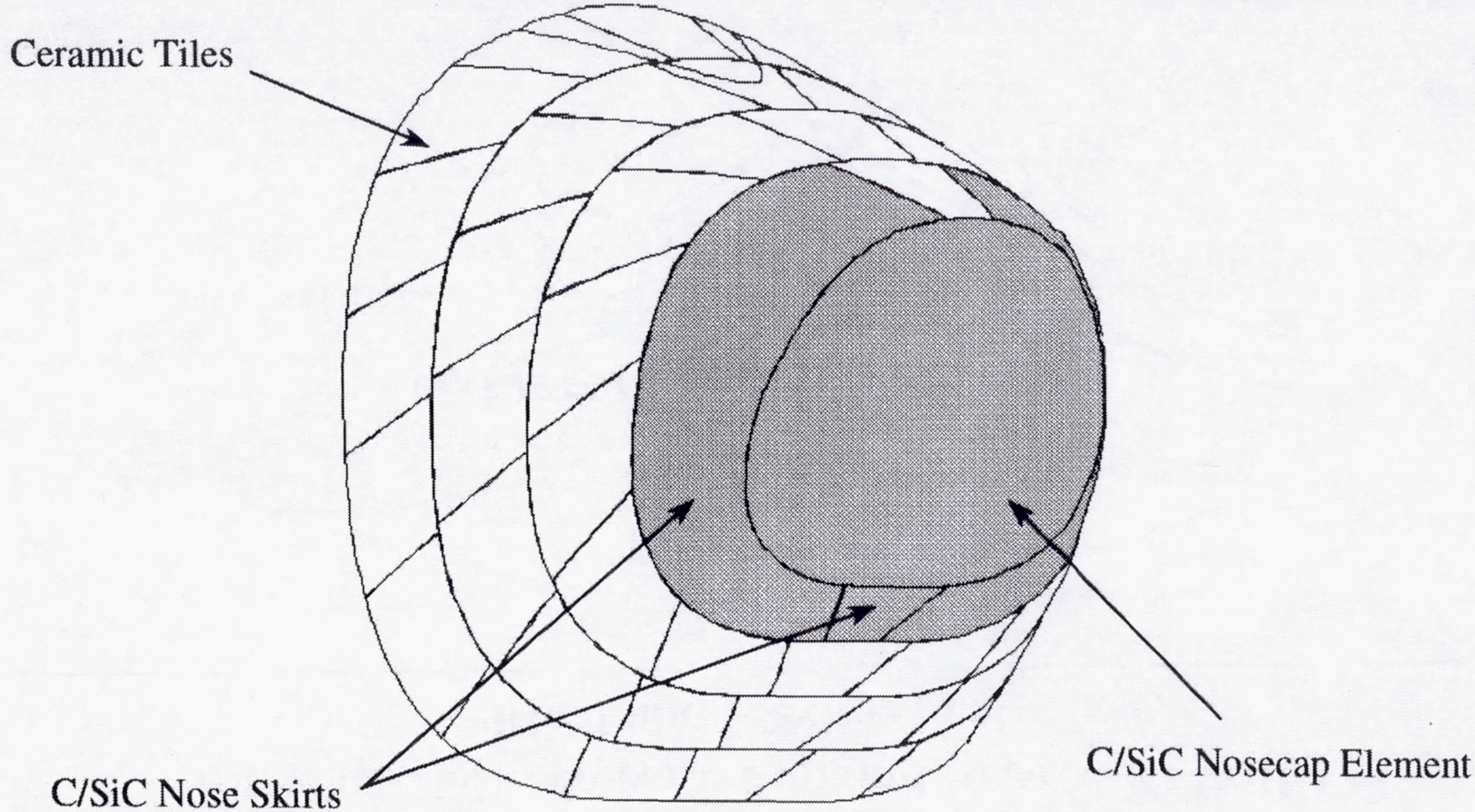
Backup Charts
Showing Additional Seal Locations

Seal Design

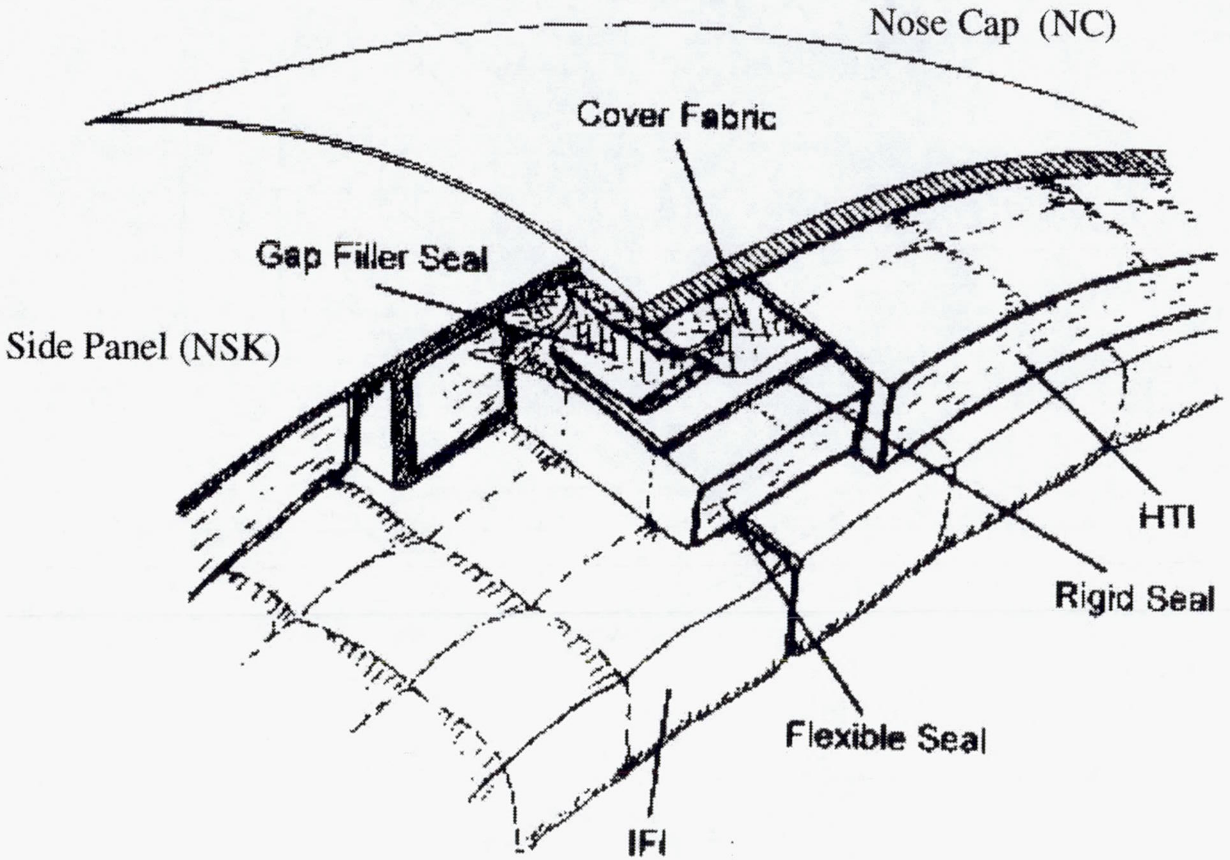
- **Chute line TPS**
  - To protect for blanket failure, a redundant system is incorporated to protect the parachute lines



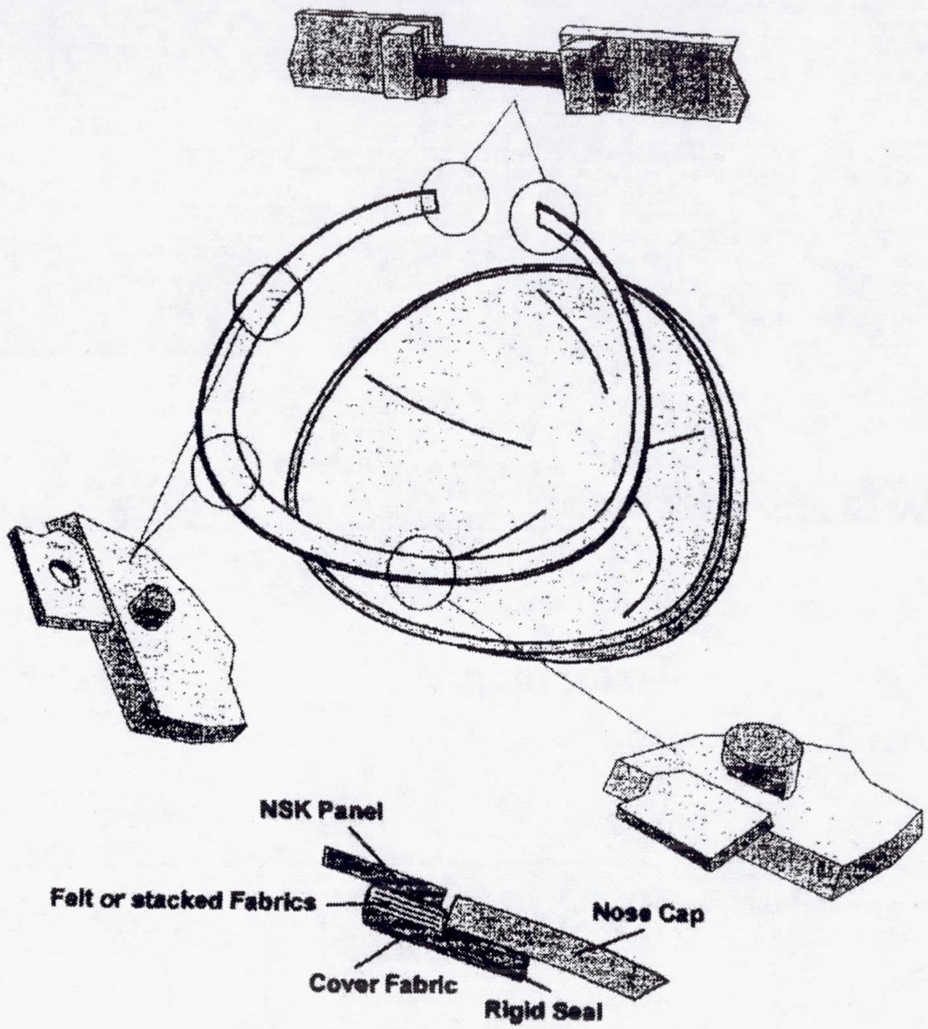
Nosecap TPS



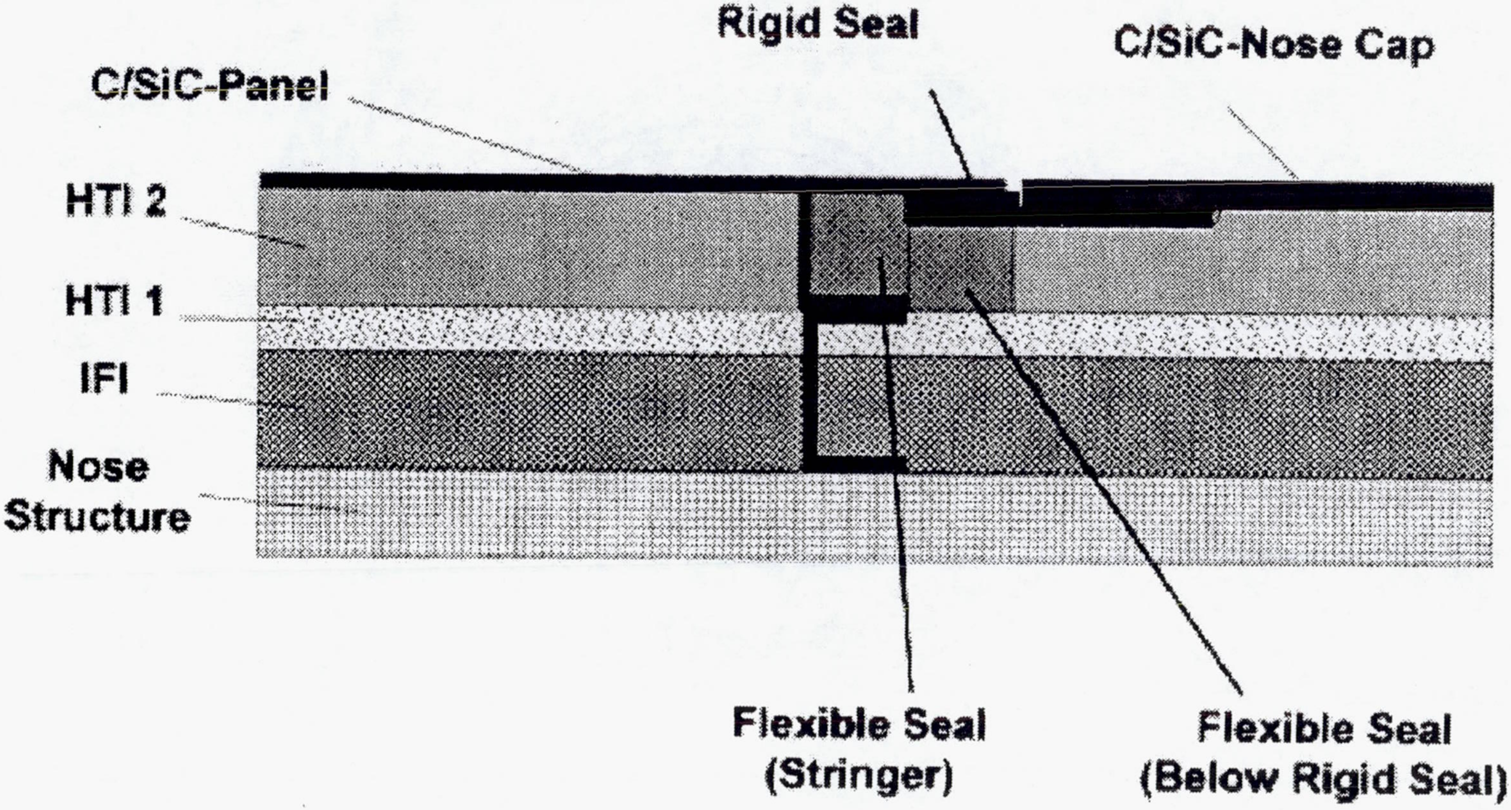
Interface Between Nose Cap and Nose Skirt With Rigid and Flexible Seal



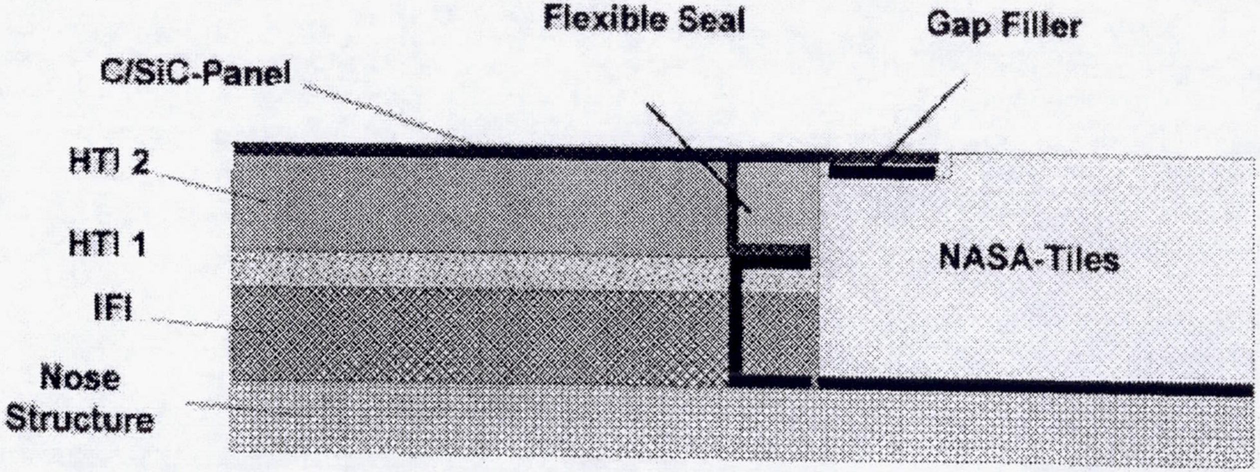
Fixation Concept of the Rigid Seal Between NC and NSK



Chin Panel / Slide Panel



I/F NSK/Thruster Tile



A PRIMER IN ADVANCED FATIGUE LIFE PREDICTION METHODS

Gary R. Halford
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio

A Primer in Advanced Fatigue Life Prediction Methods

Gary R. Halford
NASA Glenn Research Center

1999 NASA Seals/Secondary Air System Workshop

Cleveland, Ohio
October 28-29

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A Primer in Advanced Fatigue Life Prediction Methods

Gary R. Halford, NASA Glenn Research Center

Abstract

Metal fatigue has plagued structural components for centuries, and it remains a critical durability issue in today's aerospace hardware. This is true despite vastly improved and advanced materials, increased mechanistic understanding, and development of accurate structural analysis and advanced fatigue life prediction tools. Each advance is quickly taken advantage of to produce safer, more reliable, more cost effective, and better performing products. In other words, as the envelop is expanded, components are then designed to operate just as close to the newly expanded envelop as they were to the initial one. The problem is perennial.

The economic importance of addressing structural durability issues early in the design process is emphasized. Tradeoffs with performance, cost, and legislated restrictions are pointed out. Several aspects of structural durability of advanced systems, advanced materials and advanced fatigue life prediction methods are presented. Specific items include the basic elements of durability analysis, conventional designs, barriers to be overcome for advanced systems, high-temperature life prediction for both creep-fatigue and thermomechanical fatigue, mean stress effects, multiaxial stress-strain states, and cumulative fatigue damage accumulation assessment.

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OUTLINE

0 - SETTING THE STAGE

- Cost of Elimination of Failure Modes
- Structural Durability - Vs. Performance - Vs. Cost
  - -- Durability, the poor step child
  - -- Life prediction - a perennial problem (local vs. global)
  - -- Prediction vs. verification dilemma

0 - GLENN DURABILITY LIFING MODELS

- *Specific Material Models(for example, Oxidation, Coatings, Brittle Materials, etc.)*
- *Multi-Factor Approach*
- *Damage Mechanics Models*
- *Fatigue Crack Growth Models*
- Fatigue Crack Initiation/Early Growth Models
  - -- Estimating Fatigue Curves (LCF & HCF)
  - -- Modeling Effects of Variables
    - - Mean stresses
    - - Notches
    - - Multiaxiality
    - - Cumulative Fatigue Damage
    - - Creep-Fatigue
    - - Thermomechanical Fatigue
  - -- Probabilistic Assessment of Non-Linear Effects

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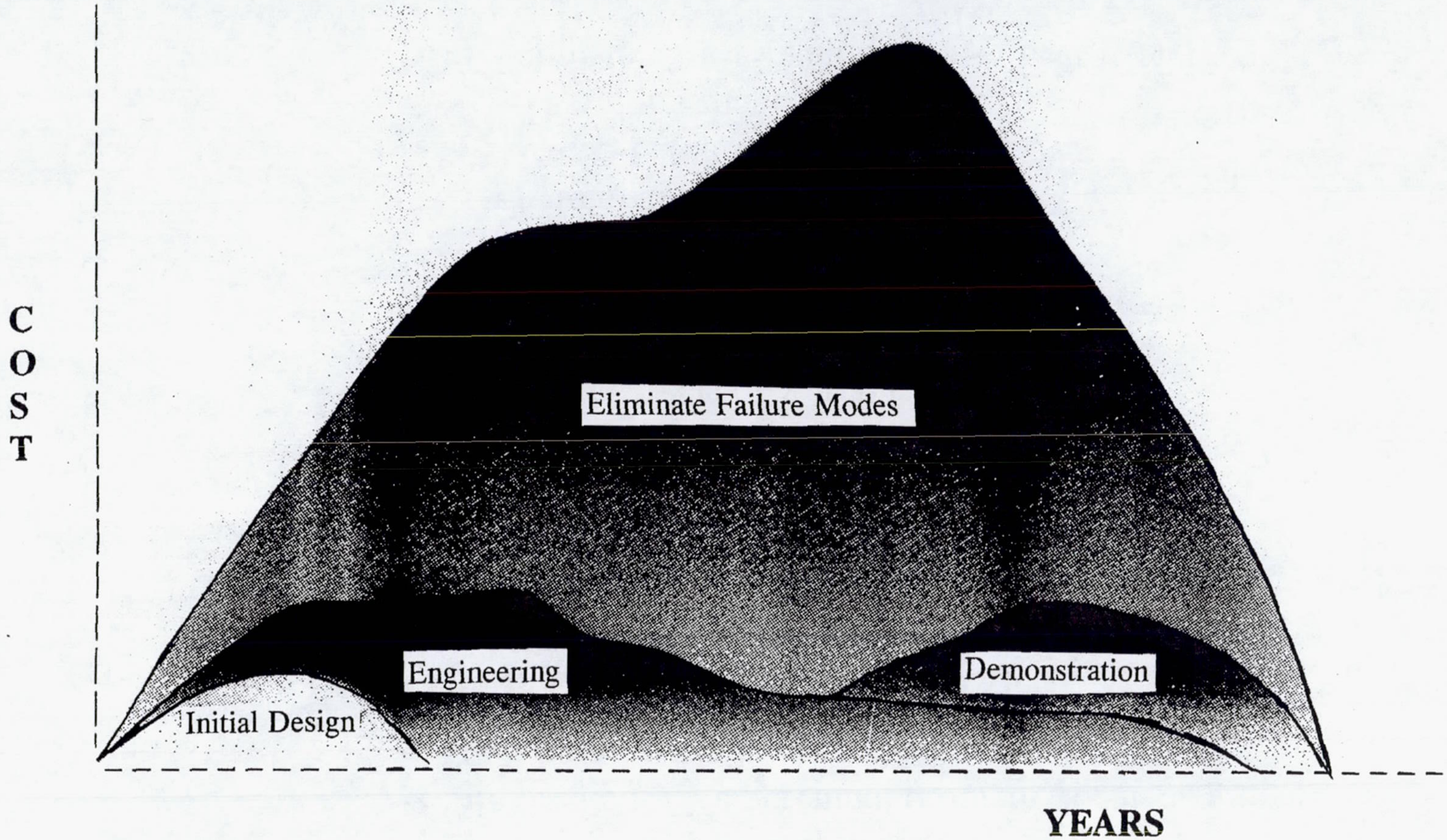
DEVELOPMENT COSTS DRIVEN BY FAILURES



COST FACTORS

Elimination Failure Modes	73%
Engineering	15%
Demonstration	10%
Initial Design	2%

Fig. Courtesy: Rockwell International

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Primary Trade-off Troika Drivers

⇑

PERFORMANCE

DURABILITY ⇒

COST

⇓

Overriding Requirements
- Legislated or Public Outcry

⇑ ⇑

⇐SAFETY & ENVIRONMENTAL ⇒

⇓ ⇓

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Elements of Durability Analyses

0 - Mission and Environmental Loading Analysis

0 - Global Structural Response Analysis

0 - Internal Stress-Strain-Temp-Time Material Response Analysis

0 - Durability Failure Modes Analysis

0 - Damage Accumulation and Life Prediction Analysis

0 - Coupon & Hardware Testing for Model Calib./Valid./Verif.

0 - Mfg Quality Analysis and Non-Destructive Evaluation (NDE)

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PEDESTRIAN DESIGNS

0 - Previous design experience

0 - Directly applicable rules of thumb

0 - Previous mission experience on similar hardware

0 - Extensive material property data bases

0 - Knowledge of all potential failure modes

0 - Knowledge of synergistic durability interactions

0 - Affordable 'build-em' and bust-em' prototypes

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BARRIERS TO ASSURED DURABILITY OF ADVANCED SYSTEMS

0 - Lack of previous direct experience/rules of thumb

0 - Limited material property data bases
-- long-term data bases unachievable in timely manner

0 - Ignorance of failure modes/synergistic interactions

0 - Low fidelity of damage accumulation/life models

0 - Prototypes too expensive to test

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SURMOUNTING THE BARRIERS

0 - Accept up-front costs of designed-in durability

0 - Require critical minimum data bases
-- early initiation of long-term testing

0 - Seek out failure modes & any synergism

0 - Capture the "physics" of damage accumulation

0 - Analytically model damage/life prediction

0 - Maximize durability information from each test

0 - Continuously update analytic models

0 - Take full advantage of probabilistic analyses

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Glenn Program	Description
-PMUS	***Estimates Fatigue Resistance of Materials*** - Tensile Ductility & Tensile Strength - Cryogenic, Ambient, High Temperatures (10% Rule)
-LIFE	***Predicts Cyclic Life of Components Below Creep Regime*** - Multiaxiality via Triaxiality Factor - Mean Stress Correction
-PNOTCH	***Predicts Cyclic Life of Notched Components*** - Cyclic Stress-Strain Neuber Notch Analysis
-PDLDR	***Predicts Cumulative Damage Life of Components*** - Mission Loading History Analyzed - Predicts Crack Nucleation & Early Growth - Double Linear Damage Rule for Mission - Multiaxiality via Triaxiality Factor - Mean Stress Correction
-C-LIFE	***Predicts Cyclic Life of C-Section Components*** - Multiaxiality via Triaxiality Factor
-PSRPLIFE	***Predicts Cyclic Life at Identified Critical Sections of High Temperature Components*** - Utilizes Raw Experimental Data. - Total Strain Version of Strainrange Partitioning (SRP) - Isothermal Creep-Fatigue Interaction Assessment - Thermomechanical Fatigue Life Prediction - Bithermal Characterization - Cyclic Stress-Strain-Time-Temperature Characterization - Multiaxiality via Triaxiality Factor - Thermal Mean Stress Correction

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Ensuring Structural Durability/Reliability of Advanced Structural Systems and Materials Will Require:

0 - Less Reliance on Past Systems/Materials Experience
0 - More Reliance on Analyses
0 - More Reliance on Understanding the Physics (Cause & Effect)
0 - Maximizing Information from each and every Test by Analysis
0 - Take Full Advantage of Probabilistic Analyses
0 - Greater Extrapolations
0 - Greater Expense
0 - Acceptance of Greater Risk until Systems Mature

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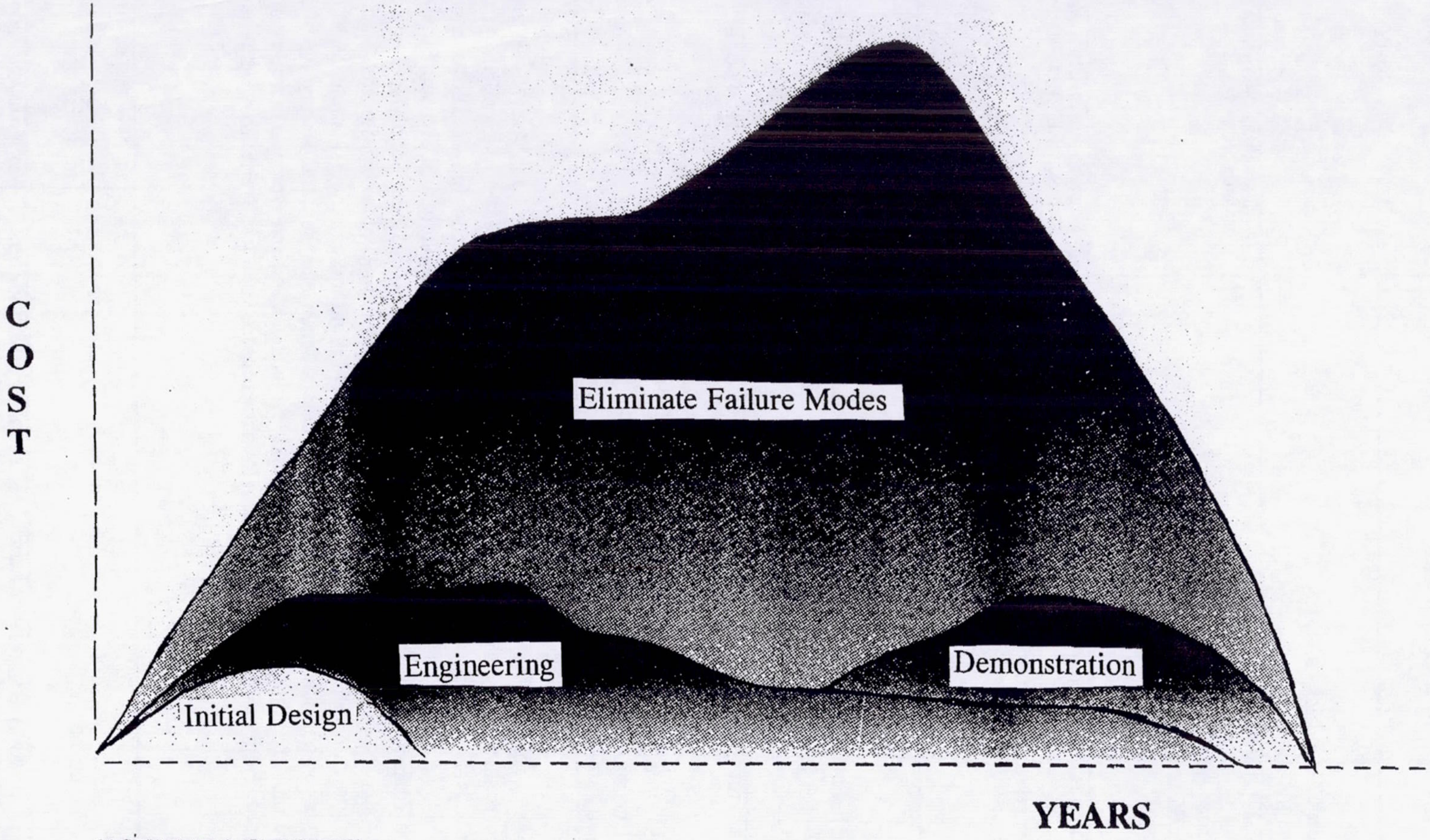
DEVELOPMENT COSTS DRIVEN BY FAILURES



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13. ABSTRACT ***(Maximum 200 words)***

NASA Glenn hosted the Seals/Secondary Air System Workshop on October 28–29, 1999. Each year NASA and our industry and university partners share their respective seal technology development. We use these workshops as a technical forum to exchange recent advancements and "lessons-learned" in advancing seal technology and solving problems of common interest. As in the past we are publishing two volumes. Volume 1 will be publicly available and volume 2 will be restricted under International Traffic and Arms Regulations (I.T.A.R.). The 1999 NASA Seal/Secondary Air System Workshop was divided into four areas; (i) overviews of the government-sponsored gas turbine programs (NASA Ultra Efficient Engine Technology program and DOE Advanced Turbine System program) and the general aviation program (GAP) with emphasis on program goals and seal needs; (ii) turbine engine seal issues from the perspective of an airline customer (i.e., United Airlines); (iii) sealing concepts, methods and results including experimental facilities and numerica predictions; and (iv) reviews of seal requirements for next generation aerospace vehicles (Trailblazer, Bantam and X-38).

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